Protecting Conifers from Bark Beetles (Coleoptera: Curculionidae, Scolytinae) with Insecticides in the Western United States[1]

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Abstract Bark beetles (Coleoptera: Curculionidae, Scolytinae) cause extensive tree mortality in conifer forests in the western United States. One method to protect conifers from bark beetles involves applications of liquid formulations of insecticides to the tree bole using high-pressure (e.g., ≥2,241 kPa) ground-based sprayers. Several active ingredients and products are effective when properly applied in accordance with the label. Researchers recently have developed more portable methods that inject small quantities of systemic insecticides directly into trees. The purpose of this review is to synthesize information on the efficacy, residual activity, and environmental safety of insecticides commonly used to protect conifers from bark beetles in the western United States so that informed, judicious decisions can be made about the use of these insecticides. This review serves as an update to “Advances in insecticide tools and tactics for protecting conifers from bark beetle attack in the western United States” (Fettig et al. 2013a) and focuses, where applicable, on relevant literature published since 2012.

Key Words bole sprays, *Dendroctonus*, *Ips*, tree injection, tree protection

Bark beetles (Coleoptera: Curculionidae, Scolytinae) are important disturbances in conifer forests. Since 2000, billions of conifers across tens of millions of hectares have been killed by bark beetles in western North America (Fettig et al. 2022a). Several recent infestations are among the largest and most severe in recorded history and have been attributed, in part, to the direct and indirect effects of climate change on bark beetles and their hosts (Bentz et al. 2010, Robbins et al. 2022) and an abundance of suitable, susceptible hosts (Fettig et al. 2022a). Each bark beetle species exhibits unique host preferences, life history traits, and impacts, but many prefer to colonize larger-diameter trees growing in dense stands with a high proportion of host type (Fettig et al. 2007). At endemic levels, bark beetles create small gaps in the forest canopy by killing individual trees or

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small groups of trees. Outbreaks can result in high (>50%) tree mortality affecting many ecosystem goods and services at local to regional scales (Table 1).

Host searching, host selection, and host colonization are complex processes in bark beetles. In general, bark beetles must detect and locate the correct habitat, correct host tree species, and the most susceptible trees within these host species (Borden 1997). When a tree is accepted by the beetle, the beetle bores through the bark and initiates gallery construction in the phloem. Some bark beetle species then release aggregation pheromones that attract other bark beetles of the same species to that tree. Successful colonization of living hosts requires overcoming tree defenses (Franceschi et al. 2005), which in the case of vigorous hosts is accomplished by recruiting large numbers (hundreds to thousands) of beetles to mass attack the tree and overwhelm its defenses. Some bark beetle species release antiaggregation pheromones during the latter phases of host colonization, presumably to reduce competition among beetles within the host tree (Borden 1997). Following completion of the life cycle and emergence from the host, progeny beetles initiate searches for new hosts. Life cycles may be completed once every 1–3 yr or multiple times per year.

Although bark beetles are a natural part of the ecology of many conifer forests, the socioecological impacts of outbreaks can be substantial (e.g., Fettig 2019; Morris et al. 2017, 2018). Several tactics are available to manage bark beetle infestations and to reduce associated tree mortality. Direct control involves short-term tactics designed to address current infestations and includes the use of sanitation harvests, insecticides, semiochemicals, or combinations of these and other treatments (Fettig and Hilszczański 2015). Indirect control involves manipulating stand, forest, and/or landscape conditions by reducing the number of susceptible hosts through thinning, prescribed burning, or other treatments (Fettig and Hilszczański 2015). Here, we review methods for protecting conifers from bark beetles with insecticides in the western United States. This review updates work by Fettig et al. (2013a) and focuses, where applicable, on relevant literature published since 2012.

Preventative Treatments

Preventative treatments involve topical sprays to the tree bole (bole sprays) or systemic insecticides injected directly into the tree (tree injections). Systemic insecticides applied to the soil have not been widely evaluated, but most evidence suggests they are ineffective (Fettig et al. 2013a). Treatments are generally limited to high-value individual trees growing in unique environments or under unique circumstances, including trees in progeny tests, seed orchards, and residential, recreational (e.g., campgrounds and ski resorts), and administrative sites. Trees genetically resistant to some forest diseases may also be treated to improve their likelihood of survival. For example, sugar pines, *Pinus lambertiana* Douglas, resistant to white pine blister rust may be treated to protect them from the mountain pine beetle, *Dendroctonus ponderosae* Hopkins. Although white pine blister rust can be fatal to all species of white pine, a gene present at low frequency occurs in *P*. *lambertiana* and confers immunity to *Cronartium ribicola* J. C. Fisch, the causal agent of white pine blister rust (Kinloch et al. 1970). Restoring populations of *P*.

Table 1. Notable bark beetles that cause mortality of conifers in the western United States. Preventative treatments have been widely studied for only *Dendroctonus brevicomis, D. ponderosae,* and *D. rufipennis*.

Common Name	Scientific Name	Common Host(s)
Arizona five-spined ips	*Ips lecontei*	*Pinus ponderosa*
California five-spined ips	*I. paraconfusus*	*P. contorta, P. lambertiana, P. ponderosa*
Douglas-fir beetle	*Dendroctonus pseudotsugae*	*Pseudotsuga menziesii*
Eastern larch beetle	*D. simplex*	*Larix laricina*
Fir engraver	*Scolytus ventralis*	*Abies concolor, A. grandis, A. magnifica*
Jeffrey pine beetle	*D. jeffreyi*	*P. jeffreyi*
Mountain pine beetle	*D. ponderosae*	*P. albicaulis, P. contorta, P. flexilis, P. lambertiana, P. monticola, P. ponderosa*
Northern spruce engraver	*I. perturbatus*	*Picea glauca, Pi.* x *lutzii*
Pine engraver	*I. pini*	*P. contorta, P. jeffreyi, P. lambertiana, P. ponderosa*
Pinyon ips	*I. confusus*	*P. edulis, P. monophylla*
Roundheaded pine beetle	*D. adjunctus*	*P. arizonica, P. engelmannii, P. flexilis, P. leiophylla, P. ponderosa, P. strobiformis*
Southern pine beetle	*D. frontalis*	*P. engelmannii, P. leiophylla, P. ponderosa*
Spruce beetle	*D. rufipennis*	*Pi. engelmannii, Pi.* x *lutzii, Pi. glauca*
Western balsam bark beetle	*Dryocoetes confusus*	*A. lasiocarpa*
Western pine beetle	*D. brevicomis*	*P. coulteri, P. ponderosa*

lambertiana involves, among other factors, selective breeding of material collected from rust-resistant trees in the wild, propagation, and eventual outplanting of rust-resistant seedlings. During large-scale bark beetle outbreaks, such as those experienced in the early 21st century (Fettig et al. 2022a), hundreds of thousands of trees may be treated in the western United States (Fettig et al. 2013a). Preventative treatments are often no longer necessary once an outbreak subsides.

Insecticides may also be used to create baited lethal trap trees in which trees treated with bole sprays are baited to attract and induce mortality of adult beetles upon contact with the bark (Fettig and Hilszczański 2015). Hansen et al. (2016) found that Engelmann spruce, *Picea engelmannii* Parry ex. Engelmann, within 30 m of baited lethal trap trees had a lower probability of severe infestation by spruce beetle, *Dendroctonus rufipennis* (Kirby), in Utah but a higher probability of severe infestation compared with the unbaited control. Thus, the authors argued against the use of baited lethal trap trees alone for management of *D. rufipennis*. Negrón et al. (2019) reached a similar conclusion based on their research on *D. rufipennis* in Colorado. Baited lethal trap trees are not widely used in the western United States.

Registration, Site Uses, and Related Information

Insecticide sales and uses in the United States are regulated by federal (U.S. Environmental Protection Agency [EPA]) and state (e.g., California Department of Pestcide Regulation) agencies. Therefore, product availability and use differ by state. The EPA regulates all pesticides under broad authority granted in two statutes: (1) the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), which requires all pesticides sold or distributed in the United States to be registered; and (2) the Federal Food, Drug and Cosmetic Act, which requires the EPA to set tolerances for pesticide used in or on food. The EPA may authorize limited use of unregistered pesticides or pesticides registered for other uses to address emergency situations, research needs, or special local needs. Under Section 5 of the FIFRA, the EPA may issue experimental use permits that allow for field testing of new pesticides or uses. Section 18 of the FIFRA permits the unregistered use of a pesticide in a specific geographic area for a limited time when an emergency pest condition exists. Under Section 24(c) of the FIFRA, states may register a new pesticide product for any use or a federally registered product for an additional use as long as a special local need is clearly demonstrated.

A list of products used as preventative treatments is beyond the scope of this review as availability changes due to cancellations, voluntary withdraws, nonpayment of registration maintenance fees, and registration of new products. Many studies have been published on the efficacy and residual activity of products that are no longer registered or have never been registered. Thus, we limit discussion to the most commonly used and extensively studied active ingredients and products. A list of products registered as preventative treatments can be obtained online from state regulatory agencies. For example, in California consult the Product/Label database of the California Department of Pesticide Regulation (https://apps.cdpr.ca.gov/docs/label/labelque.cfm). This database contains up-to-date information on all pesticide products registered in California and includes the registrant's name and address, active ingredients, site/pest category uses, pesticidal type, formulation code, and registration status. Information is updated at midnight each business day. Kelly Products provides similar information in an easily accessible format for most but not all states (https://www.kelly-products.com/licensing-renewals/#). Greenbook provides easily accessible downloads of labels and safety data sheets (https://www.greenbook.net/).

All insecticides registered and sold in the United States must carry a label, and it is a violation of federal law to use any product in a manner inconsistent with its label. The label contains abundant information concerning safe and appropriate uses (e.g., signal words, first aid and precautionary statements, and proper mixing). For products used in tree protection, users should note whether the product is registered for use on ornamentals and/or in Christmas tree plantations, forest plantations, and forests. Applications must be limited to the appropriate site(s). Prior to using insecticides, users should confirm the registration status in the state of use and carefully read the label. Follow all instructions on the label, including those pertaining to the use of personal protective equipment during mixing, handling, and application. The Occupational Safety and Health Administration requires that safety data sheets be available for potentially harmful substances handled in the workplace. Although labels and safety data sheets contain some of the same information, safety data sheets focus on hazards in occupational settings.

Experimental Designs for Evaluating Preventative Treatments

The most common experimental design for evaluating preventative treatments is the baited-tree assay, in which insecticides are applied to an experimental population of trees. These trees and a set of untreated trees (controls) are baited with species-specific attractants. Efficacy and residual activity are determined based on tree mortality and established statistical parameters (Shea et al. 1984) or other analyses. Protocols established by Shea et al. (1984) and widely used since require sufficient beetle pressure ($\geq$60% mortality) in the control to make inferences regarding the efficacy or residual activity of insecticides. Insecticide treatments are considered efficacious when six or fewer trees die due to bark beetle attack. This criterion was established based on a sample size of 22–35 trees per treatment (Shea et al. 1984). The baited-tree assay is accepted as the standard for evaluating preventative treatments in the western United States and provides a conservative test via baiting. However, these assays are laborious, expensive, and time-consuming (e.g., efficacy is often monitored for two or three field seasons, defined as the period of the majority of flight activity of the target species for a given year). During evaluations of bole sprays, care must be taken to avoid drift onto adjacent experimental trees, which requires large study areas to accommodate reasonable sample sizes. During evaluations of tree injections, separation (e.g., $>$10 m) among experimental trees may be important to reduce the likelihood that root grafts will translocate systemic insectcides, although this relationship has not been well studied.

Some researchers have argued that the baited-tree assay is too conservative. In most cases baits are left on trees throughout the field season, yet under natural conditions attractants (i.e., aggregation pheromones) are not released from unattacked trees or not released from attacked trees for such lengthy periods (months). This concern can be alleviated by regular monitoring (e.g., weekly) of the baited controls for bark beetle attacks and removal of baits from all experimental trees when the baited controls appear to have reached sufficient attack densities (e.g., >50 beetles/m^2) to induce tree mortality. However, regular monitoring adds considerable cost to the assay. Baiting may result in adjacent untreated trees being colonized and killed by bark beetles (spillover), which may be of concern in some circumstances. Effective attractants have not been identified and developed for all bark beetle species (e.g., fir engraver, *Scolytus ventralis* LeConte), limiting evaluations of preventative treatments for these species.

Variants of the baited-tree asssay include the hanging-bolt assay (Berisford et al. 1980) and small-bolt assay (Strom and Roton 2009) in which insecticides are applied to uninfested trees that are later harvested and cut into bolts for inclusion in field or laboratory experiments. Efficacy is determined based on measures of attack density or gallery construction. Compared with the baited-tree assay, the hanging-bolt assay and small-bolt assay allow for rapid acquisition of data, reduced risk of loss of scientific infrastructure (e.g., to wildfire), and increased probability that a rigorous test will be achieved because bolts are transported to active infestations in the field or exposed to beetles in the laboratory. Although these designs account for some host factors (e.g., bark architecture), others such as host defenses are ignored. These assays also do not provide an estimate of tree mortality. As a result, the hanging-bolt assay and small-bolt assay are not widely used in the western United State.

Laboratory assays require trapping of live adult bark beetles (e.g., using multiple-funnel traps baited with species-specific lures) or rearing of live adult bark beetles from infested host materials. Crumpled paper towels placed at the bottom of collection cups reduce the number of beetles that escape multiple-funnel traps and decrease damage to and predation of individuals collected (Fettig et al. 2011). Beetles that are damaged (e.g., loss of any appendages), weakened, or not used within 48 h of collection should not be assayed. Generally, serial dilutions of each insecticide are prepared and evaluated in filter paper or topical assays (Fettig et al. 2011). In filter paper assays, a small quantity (~1 ml) of insecticide solution is applied to a microfiber filter disc stored in a petri dish. The filter paper is allowed to dry before test subjects are placed on it. In topical assays, a small quantity (e.g., 0.5 μl) of insecticide solution is applied to each bark beetle (e.g., on the mesothorax), and the beetle is transferred to a petri dish. The life table method (Lee and Wang 2003) is used to estimate the survival probability of test subjects in response to different doses of each insecticide. Laboratory assays ignore important environmental factors (e.g., temperature, humidity, and sunlight) and host tree factors (e.g., architecture and defenses) that influence efficacy and residual activity under field conditions. However, results can be rapidly obtained and at lower costs than baited-tree, hanging-bolt, and small-bolt assays. The primary use of laboratory assays is to screen the toxicity of new active ingredients or products before investing in baited-tree assays.

Bole Sprays

Bole sprays are still the most common insecticide treatment despite substantial advances in tree injection in the last 15 yr (see “Tree Injection” below). Beetles contact the toxicant on the bark surface before entering the tree. Most bole sprays

Fig. 1. Bole sprays are commonly used to protect conifers from bark beetles in the western United States. Photos: C.J.F.

are applied in late spring or early fall with ground-based sprayers at high pressure (e.g., ≥2,241 kPa) from the root collar to midcrown until runoff (Fig. 1). On very tall trees (e.g., >33 m in height), sprayers may be incapable of reaching the midcrown, leaving upper portions of the bole unprotected and vulnerable to colonization by bark beetles. In these cases, a bucket truck or lift may be necessary to facilitate bole sprays. For some engraver beetles, *Ips* species, branches >5 cm in diameter should also be treated (e.g., for pinyon ips, *Ips confusus* [LeConte]) (Fettig et al. 2006a). The amount of solution (product + water) applied differs with bark and tree architecture, tree size, equipment, applicator, and other factors but generally is ~15–30 L/tree (DeGomez et al. 2006; Fettig et al. 2006a, 2006b, 2008). Application efficiency, that is, the percentage of material applied that is retained on trees, ranges from ~80–90% (Fettig et al. 2008, Haverty et al. 1983). Failures in efficacy are rare and typically associated with inadequate coverage and/or improper mixing (e.g., using an alkaline water source with pH >8), improper storage (e.g., under excessive heat or cold), and improper timing (e.g., applying treatments to trees already colonized by bark beetles). We suggest that (a) applicators spray trees that are <31 cm diameter at breast height (dbh; 1.37 m high) from at least three faces (positions) and trees that are ≥31 cm dbh from at least four faces to help ensure adequate coverage of the bole; and (b) applicators procure and properly store tank samples, which can later be analyzed for concentration if failures in efficacy are observed.

A disadvantage of bole sprays is that they require transportation of heavy equipment in the field, which can be problematic in western forests where snow drifts and poor road conditions often limit access in spring and early summer. Many campgrounds where bole sprays are frequently applied are located near intermittent or ephemeral streams that are associated with spring runoff, limiting applications due to restrictions imposed by no-spray buffers to protect nontarget aquatic organisms (Table 2). Extension bulletins are available to assist applicators and resource managers with bole sprays (DeGomez 2011, Fettig et al. 2014b, Munson et al. 2011).

Table 2. Factors informing selection of bole sprays and tree injections as preventative treatments for bark beetle in the western United States. Descriptions are based on an effective insecticide properly applied by skilled applicators under normal field conditions.

Factor	Bole Sprays	Tree Injections
Access	Limited, requires transporting large heavy equipment (trucks and sprayer trailers). In most cases, treated trees must be <100 m from the sprayer.	Equipment can be carried by hand in a tote or bucket.
Cost	Low	High
Drift and nontarget effects	Application efficiency is ~80–90%. Most drift (97%) lands within 15.2 m of the tree bole. No-spray buffers may be required near sensitive sites, such as streams, limiting the number and distribution of trees that can be treated.	Essentially closed systems with little contamination occurring outside of the treated tree.
Efficacy	High. In some cases, sprays may not reach high enough to treat all vulnerable portions of the bole of very tall (>33 m) trees. During severe outbreaks, this may result in top-kill.	High
Efficiency	Few minutes per tree	Generally, 3–30 min per tree but occasionally longer under suboptimal conditions. Considerable time is often required for uptake of systemic injections in conifers, which depends on the rate of transpiration as influenced by air and soil temperatures, short-wave radiation, relative humidity, and soil moisture (Collatz et al. 1991).

Table 2. Continued.

Factor	Bole Sprays	Tree Injections
Mixing	Requires large amounts of water. Quantity of solution (product + water) applied differs with bark and tree architecture, tree size, equipment, applicator, and other factors but generally is ∼15–30 L/tree.	Limited or none. A few hundred milliliters of product is used to treat the largest of trees.
Mode	Beetles contact toxicant on the bark surface.	Beetles contact toxicant in the phloem. Insecticides can be mixed and injected in solution with fungicides, which limit the distribution of blue stain fungi in treated trees. Blue stain fungi are vectored by bark beetles and can have deleterious effects on tree health.
Personal protective equipment (PPE)	Variable, see label. Generally, more PPE is required for mixers and loaders.	Variable, see label.
Portability	Requires transporting large heavy equipment (trucks and sprayer trailers). A bucket truck or lift may be necessary to facilitate bole sprays on very tall trees.	Equipment can be carried by hand in a tote or bucket.
Phytotoxicity	None	To our knowledge, phytotoxic effects have been reported in only one tree (treated with abamectin + tebuconazole; Fettig et al. 2013b).
Residual activity	Generally one or two field seasons	Generally two or three field seasons
Technical expertise required	Moderate	High

Table 2. Continued.

Factor	Bole Sprays	Tree Injections
Timing of treatments	Simple	Complex, varies with beetle–host system (Table 4).
Tree damage	None	Damage occurs during injections (e.g., via drilling and insertion of plugs into the tree) but is minimal. Damage may limit treatment of small trees (e.g., ≤15 cm dbh; Fettig et al. 2013b).
Weather	Excessive wind and rain limit when bole sprays can be applied.	Injections can be made at any time as long as trees are actively translocating materials.

Carbaryl

Carbaryl is an acetylcholinesterase inhibitor that prevents the cholinesterase enzyme 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. Carbaryl is essentially nontoxic to birds, moderately toxic to mammals, fish, and amphibians, and highly toxic to honeybees, *Apis mellifera* L., and some aquatic insects (Durkin and King 2008). Several products containing carbaryl are commonly used to protect conifers from bark beetles, and carbaryl is the most extensively studied active ingredient registered for this use.

Mountain and western pine beetles. Several rates and formulations of carbaryl have been evaluated against *D. ponderosae* and western pine beetle, *D. brevicomis* LeConte, with most research indicating two field seasons of protection can be expected with a single application (Table 2). The effectiveness of 1.0% and 2.0% (percent active ingredient) carbaryl (e.g., Sevimol®, Union Carbide, Research Triangle Park, NC) was demonstrated in the early 1980s. This and other research led to the registration of 2.0% Sevimol as a preventative spray; however, registration was voluntarily canceled in 2006. Shea and McGregor (1987) evaluated the efficacy and residual activity of 0.5%, 1.0% and 2.0% carbaryl (Sevimol and Sevin® XLR, Union Carbide) and found that all concentrations and formulations were effective for protecting lodgepole pine, *Pinus contorta* Douglas ex Loudon, from *D. ponderosae* for one field season in Montana. The 1.0% and 2.0% formulations were effective for two field seasons. Fettig et al. (2006a) reported that 2.0% carbaryl (Sevin SL, Bayer CropScience, Research Triangle Park, NC) protected ponderosa pine, *Pinus ponderosa* Douglas ex Lawson, from *D. brevicomis* in California, *P. ponderosa* from *D. ponderosae* in South Dakota, and *P. contorta* from *D. ponderosae* in Montana (two separate studies) for two field seasons. These results agree with other research in which 2.0% carbaryl (Sevin SL) protected *P. contorta* from *D. ponderosae* for two field seasons in Montana (Fettig et al. 2006b).

Both spring (mid-June) and fall (mid-September) applications of 2.0% carbaryl (Sevin SL) were effective for protecting *P. contorta* from *D. ponderosae* for two field seasons in Wyoming (Fettig et al. 2015). As a result, many bole sprays for protecting *P. contorta* from *D. ponderosae* are now applied in the fall when access is easier and there tends to be less competition with the agricultural sector for hiring applicators. In a similar study with *D. ponderosae* in Idaho, both spring (mid-June) and fall (early-September) treatments of 2.0% carbaryl (Sevin SL) provided only one field season of protection, and an initial fall treatment was ineffective (Fettig et al. 2018). The residual activity of carbaryl (and other insecticides) on pine bark is influenced by weather, which affects hydrolysis and microbial activity and thus degradation of carbaryl. Shorter residual activity is expected in wetter and warmer environments (Zhong et al. 1995b). In the winter following the fall treatment in the Idaho study, precipitation was above normal (Fettig et al. 2018), which could have contributed to the lack of efficacy observed.

Spruce beetle. Most research suggests that for *D. rufipennis* two or three field seasons of protection can be expected with a single application of carbaryl (Table 3). In southcentral Alaska, Werner et al. (1986) reported that 1.0% and 2.0% carbaryl (Sevin SL) protected white spruce, *Picea glauca* (Moench) Voss, and Lutz spruce, *Picea* × *lutzii* Little, from *D. rufipennis* for three field seasons. Fettig et al. (2006a) reported 2.0% carbaryl (Sevin SL) would likely protect *Pi. engelmannii* for

Table 3. Residual activity of common active ingredients used in bole sprays in the western United States. Residual activity tends to be shorter in wetter and warmer environments. Unless otherwise noted, data were obtained from baited-tree assays.

	Number of field seasons of protection*		
Bark Beetle Species	**Bifenthrin**	**Carbaryl**	**Permethrin**
Mountain pine beetle (*Dendroctonus ponderosae*)	Two	Two, fall applications (e.g., September) provide one or two depending on host; residual activity tends be shorter in ponderosa pine (*Pinus ponderosa*)	One or less; studies have yielded mixed results
Spruce beetle (*D. rufipennis*)	Two	Two or three	Two
Western pine beetle (*D. brevicomis*)	Two	Two	One
Engraver beetles (*Ips* species)	One or two, some inference drawn from small-bolt assay	One or two, some inference drawn from small-bolt assay	One, some inference drawn from small-bolt assay
Southern pine beetle (*D. frontalis*)	Less than one, inference drawn from small-bolt assay; limited data	Not effective; see Zhong et al. (1994, 1995a, 1995b) for explanations	One or less, inference drawn from small-bolt assay; limited data
Red turpentine beetle (*D. valens*)	No data	One or less, inference drawn from unbaited-tree assay; limited data	One or less, inference drawn from unbaited-tree assay; limited data

* Field seasons defined as the period of the majority of flight activity of the target species for a given year.

two field seasons in Utah. During the second field season, beetle pressure in the baited control (56% tree mortality) was insufficient to make definitive conclusions regarding efficacy (<60% tree mortality; Shea et al. 1984), yet no mortality was observed in the Sevin SL treatment.

Engraver beetles. Most research suggests that for Ips species one or two field seasons of protection can be expected with a single application of carbaryl (Table 3). An application of 2.0% carbaryl (Sevin SL) was effective for protecting single-leaf pinyon, *Pinus monophylla* Torrey & Fremont, from *I. confusus* for two field seasons in Nevada (Fettig et al. 2006a). In a similar study in pinyon pine, *Pinus edulis* Engelmann, in Colorado, Sevin SL was effective for one field season; results from a second field season were inconclusive because of insufficient beetle pressure in the baited control (<60% tree mortality; Shea et al. 1984). Fettig et al. (2006a) also evaluated 2.0% carbaryl (Sevin SL) for protecting *P. ponderosa* from pine engraver, *Ips pini* (Say), in Arizona, but few trees were attacked during the baited-tree assay. To help salvage the experiment, treated (live) trees were harvested and cut into bolts that were laid on the ground in areas containing slash infested with *I. pini*, six-spined ips, *Ips calligraphus* (Germar), and Arizona five-spined ips, *Ips lecontei* Swain (DeGomez et al. 2006). From this and related research, the authors concluded that 1.0% and 2.0% carbaryl (Sevin SL) were effective for protecting *P. ponderosa* from *Ips* species for one field season in Arizona (Table 3).

Southern pine beetle. Southern pine beetle, *Dendroctonus frontalis* Zimmerman, occurs in a near continuous distribution across the southern United States, which roughly coincides with the distribution of loblolly pine, *Pinus taeda* L., but also is endemic to Arizona and New Mexico where it colonizes several pine species. Although preventative treatments have not been evaluated for *D. frontalis* in the western United States, carbaryl is ineffective for protecting *P. taeda* from *D. frontalis* in the southern United States (Ragenovich and Coster 1974) because of an efficient conversion of carbaryl into metabolites in *D. frontalis* and a rapid rate of excretion (Zhong et al. 1994, 1995a, 1995b) (Table 3).

Red turpentine beetle. Limited research suggests that for red turpentine beetle, Dendroctonus valens LeConte, one field season of protection can be expected with a single application of carbaryl (Table 3). Dendroctonus valens colonizes the basal portions of stressed, weakened, or dead and dying trees and are not considered an important source of tree mortality in the United States. As a result, only limited research has been conducted on preventative treatments. Hall (1984) reported that 2.0% (Sevin XLR) and 4.0% carbaryl (Sevimol 4, Union Carbide) were effective for reducing attacks on *P. ponderosa* in California. Levels of tree mortality were not reported but presumably were low. Several formulations of carbaryl were effective for reducing attacks on Monterey pine, *Pinus radiata* D. Don, in California (Svihra 1995), but residual activity was less than one field season (Table 3). Levels of tree mortality were not reported but presumably no mortality occurred (i.e., mean attack densities in the controls were 6.7 and 9.4 beetles/tree).

Pyrethroids

Pyrethroids are synthesized from petroleum-based chemicals and are related to the insecticidal compounds produced by flowering *Chrysanthemum* plants. Pyrethroids are axonic poisons and cause paralysis by keeping the sodium channels open in the neuronal membranes (Gajendiran and Abraham 2018). First generation pyrethroids were developed in the 1960s but were unstable in sunlight. By the mid-1970s, second generation compounds was developed (permethrin, cypermethrin, and deltamethrin) that are more resistant to photodegradation. Third generation pyrethroids (bifenthrin, cyfluthrin, and lambda-cyhalothrin) have greater photostability and insecticidal activity than do the first and second generation pyrethroids. In general, pyrethroids are not acutely toxic to mammals, essentially nontoxic to birds, but highly toxic to fish, amphibians, and *A*. *mellifera*. Several products containing permethrin (e.g., Astro®, FMC Corp., Philadelphia, PA) and bifenthrin (e.g., OnyxPro®, FMC Corp.) are commonly used as preventative treatments and are the second most extensively studied insecticides after carbaryl.

Mountain and western pine beetles. Several active ingredients and products containing pyrethroids have been evaluated as preventative treatments for *D. ponderosae* and *D. brevicomis*. Most research suggests that at least one field season of protection can be expected with a single application (Table 3). Permethrin plus-C (Masterline®, Univar USA Inc., Austin, TX), a formulation containing methyl cellulose (the "plus-C") thought to reduce light, chemical, and biological degradation of permethrin, has efficacy and residual activity similar to those of other formulations of permethrin for protecting *P*. *contorta* from *D*. *ponderosae*. Fettig et al. (2006b) reported that 0.2% permethrin plus-C (Masterline) protected *P*. *contorta* from *D*. *ponderosae* for one field season in Montana while 2.0% carbaryl (Sevin SL) was effective in the same assay for two field seasons. Early research on bifenthrin evaluated 0.03%, 0.06%, and 0.12% (Onyx™, FMC Corp.) and reported a minimum of one field season of protection for *P*. *contorta* from *D*. *ponderosae* in Montana and two field seasons for *P*. *ponderosa* from *D*. *brevicomis* in California. These results resulted in registration of 0.06% Onyx as a preventative spray in the mid-2000s. In a 3-yr study in California, 0.06% bifenthrin (Onyx) failed to protect *P*. *ponderosa* from *D*. *brevicomis* during a third field season (Grosman et al. 2010b). In the laboratory, Rivera-Dávila et al. (2022) evaluated bifenthrin, deltamethrin, and cypermethrin in topical assays on the smaller Mexican pine beetle, *Dendroctonus mexicanus* Hopkins, and found that bifenthrin was the most toxic of these active ingredients.

Spruce beetle. Most research suggests that for *D. rufipennis* at least one field season of protection can be expected with a single application (Table 3). Fettig et al. (2006a) reported that 0.03%, 0.06%, and 0.12% bifenthrin (Onyx) would likely protect *Pi*. *engelmannii* for two field seasons in Utah. During the second field season, beetle pressure in the baited control (56% tree mortality) was insufficient to make definitive conclusions regarding efficacy (<60% tree mortality; Shea et al. 1984), yet no mortality was observed in the Onyx treatments. Protection of *Pi. glauca* in Alaska is possible for two field seasons with a single application of 0.25% permethrin (formulation unreported) (Werner et al. 1984).

Engraver beetles. Most research suggests that for Ips species at least one field season of protection can be expected with a single application (Table 3). However, Fettig et al. (2006a) reported that 0.03%, 0.06%, and 0.12% bifenthrin (Onyx) protected *P*. *monophylla* from *I*. *confusus* for two field seasons in Nevada. DeGomez et al. (2006) reported that 0.19% permethrin plus-C (Masterline) and 0.06% bifenthrin (Onyx) were effective for protecting *P*. *ponderosa* bolts from *Ips* species for one field season in Arizona.

Fig. 2. Recent advances in tree injection offer a viable alternative to bole sprays: Tree IV micro infusion® (left) and QUIK-jet AIR® (right) (Arborjet Inc., Woburn, MA). Following injection, the product is transported throughout the tree to the phloem, where bark beetles feed. Injections can be applied at any time of year when trees are actively translocating materials, but time is needed to allow full distribution of the active ingredient within the tree before the tree is attacked by bark beetles. Photos: D.M.G.

Southern pine beetle. To our knowledge, no studies have been conducted on the effects of pyrethroids on *D. frontalis* in the western United States. Limited research conducted in the southeastern United States suggests that 0.5% permethrin (Astro) has longer residual activity than 0.06% bifenthrin (Onyx) (Strom and Roton 2009) (Table 3). In that study, small *P. taeda* (~9 cm dbh) were sprayed to a height of ~2.5 m and left standing in the field until they were cut for inclusion in a small-bolt assay.

Red turpentine beetle. Svihra (1995) reported that 0.5% permethrin (Dragnet®, FMC Corp.) was effective for reducing *D. valens* attacks on *P. radiata* in California and that the residual activity was longer than that of 0.5% carbaryl (Sevimol 4). Levels of tree mortality were not reported but presumably were low. Hall (1984) reported that 0.1%, 0.2%, and 0.4% permethrin (formulation unreported) were ineffective for protecting *P. ponderosa* in California. In China, where *D. valens* was accidently introduced in the 1990s, cypermethrin (concentration and formulation unreported) was reported effective for killing adult *D. valens* when applied to the boles of susceptible trees (Yan et al. 2005).

Tree Injections

Research on tree injections in the 1980s–1990s indicated that several methods, active ingredients, and formulations were ineffective (Fettig et al. 2013a). Since the early 2000s, the efficacy and residual activity of phloem-mobile active ingredients injected with pressurized systems (e.g., Sidewinder® Tree Injectors, Brisbane, Queensland, Australia; Tree IV micro infusion® and QUIK-jet AIR®, Arborjet Inc., Woburn, MA; and Wedgle® Direct-Inject™, ArborSystems, Omaha, NE) capable of maintaining >275 kPA have been evaluated for several bark beetle species in the western United States (Fig. 2). After injection, the product is transported throughout the tree to the phloem, where bark beetles feed. Beetles must enter the tree to contact the toxicant. Injections can be done at any time of year when the tree is actively translocating water and nutrients, but time is required to allow for full distribution of the active ingredient within the tree before the tree is attacked by bark beetles. Under optimal conditions (e.g., adequate soil moisture, moderate temperatures, and good overall tree health) full distribution takes ~4 wk (Grosman and Upton 2006) but may take much longer (up to 1 yr) in high-elevation forests due to cold temperatures (Table 3). Tree injections utilize closed-system equipment that eliminates concerns regarding insecticide drift and reduces concerns regarding nontarget effects. These systems are very portable (Table 2). One disadvantage is that proper timing of injections is complex and differs among bark beetle–host systems (Table 3). An extension publication is available to assist applicators and resource managers with tree injections (Bernick and Smiley 2022).

Emamectin Benzoate

Emamectin benzoate is a macrocyclic lactone derived from avermectin B1 (= abamectin) by fermentation of a soil actinomycete, *Streptomyces avermitilis* Burg. This chemical disrupts neurotransmitters, causing irreversible paralysis. Emamectin benzoate is highly toxic to fish and *A*. *mellifera* and very highly toxic to aquatic invertebrates. It is highly toxic to mammals and birds on an acute oral basis but is dermally benign to mammals (Durkin 2010). Several products containing emamectin benzoate are used to protect conifers from bark beetles, and emamectin benzoate is the most extensively studied systemic insecticide registered for this use.

Mountain and western pine beetles. Grosman et al. (2010b) evaluated an experimental formulation of emamectin benzoate (Syngenta Crop Protection Inc., Greensboro, NC) mixed 1:1 with methanol for protecting *P*. *ponderosa* from *D*. *brevicomis* in California. The treatment was injected in mid-May at four cardinal points 0.3 m above the ground using the Tree IV microinfusion system at 0.2 or 0.4 g of active ingredient (a.i.) emamectin benzoate/2.54 cm dbh to trees <25 or ≥25 cm dbh, respectively. Three field seasons of protection were observed with a single injection (Table 4), and only 1 of the 30 trees treated with emamectin benzoate died during the assay. To our knowledge, this was the first demonstration of a successful application of a systemic insecticide for protecting individual trees from mortality attributed to bark beetles in the western United States. This and other research led to the registration of emamectin benzoate (4.0% a.i.; TREE-äge®, Arborjet Inc.) as a preventative treatment in 2010. The commercial formulation (TREE-äge) has not been evaluated for protecting *P*. *ponderosa* from *D*. *brevicomis* in a baited-tree assay but appears as effective as the experimental formulation of emamectin benzoate evaluated by Grosman et al. (2010b) (D.M.G., pers. obs.).

The experimental formulation of emamectin benzoate used by Grosman et al. (2010b) was ineffective for protecting *P*. *contorta* from *D*. *ponderosae* in Idaho when injected in late May and early June, which agrees with results from other baited-tree assays for *D*. *ponderosae* in British Columbia, Canada and Colorado (D.M.G. et al. unpubl. data). These results were also confirmed for the commercial formulation (TREE-äge) injected at 10 ml/2.54 cm dbh in Utah (Fettig et al. 2014a).

Table 4. Summary of appropriate timing, residual activity, and uptake of emamectin benzoate used in tree injections in the western United States. Adapted from Fettig et al. (2020).

Bark Beetle Species	Host Species	Timing, Residual Activity, and Uptake
Mountain pine beetle (*Dendroctonus ponderosae*)	Lodgepole pine (*Pinus contorta*)	Emamectin benzoate should be injected in August or September (year *X*) before flight activity the following year (year $X + 1$). By combining emamectin benzoate with propiconazole, treatments can be injected in the spring before flight activity occurs for that year (Fettig et al. 2014a). Two field seasons of protection can be expected. Uptake is generally good throughout the day, except on very sunny or windy (>25 kph) days.
Spruce beetle (*D. rufipennis*)	Engelmann spruce (*Picea engelmannii*)	Emamectin benzoate should be injected in June the year before flight activity the following year (Fettig et al. 2020) and at a narrow spacing (7.6 cm; Fettig et al. 2020). Two field seasons of protection can be expected. Uptake is generally good throughout the day.
Western pine beetle (*D. brevicomis*)	Ponderosa pine (*P. ponderosa*)	Emamectin benzoate should be injected in April or May before flight activity occurs for that year (Grosman et al. 2010a). Three field seasons of protection can be expected. Uptake is best in the morning and slows throughout the day. On hot (>26°C) sunny days, uptake can be problematic after midday.

Differences in air and soil temperatures explain the lack of efficacy observed in these assays (D.M.G. unpubl. data, Grosman et al. 2010b, Fettig et al. 2014a) compared with the *D. brevicomis* assay in California (Grosman et al. 2010b) because cold temperatures slow translocation of injectables in trees. Grosman et al. (2010b) speculated that early failures were attributed to inadequate distribution of emamectin benzoate injected just weeks prior to trees being challenged by

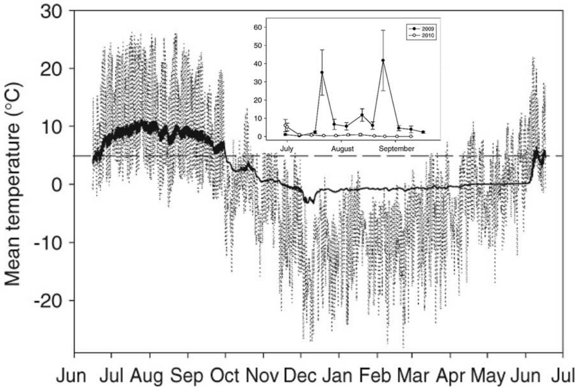

Fig. 3. Mean air (1 m) and soil (10 cm deep) temperatures at 0.5-hr intervals, Uinta-Wasatch-Cache National Forest, Utah (~2,865 m elevation), 2009–2010. Inset: mean number (±SEM) of *Dendroctonus ponderosae* caught in 16-unit multiple-funnel traps baited with *D. ponderosae* lures, Uinta-Wasatch-Cache National Forest, 2009 and 2010. Adapted from Fettig et al. (2014a).

D. ponderosae. The authors suggested that injection of trees in August or September (year *X*) before trees are challenged by *D. ponderosae* the following year (year $X + 1$; attacks usually begin in late June) would increase efficacy. Fettig et al. (2014a) later studied this relationship in a high-elevation forest in Utah (~2,865 m elevation) where mean air and soil temperatures ranged from −28.2 to 26.3°C and from −3.2 to 11.1°C, respectively (Fig. 3). Mean soil temperatures (10 cm depth) were >5°C (i.e., representing a threshold of metabolic activity suitable for effective translocation of injectables within trees) on only 107 d (Fig. 3; primarily July, August, and September). In California, Doccola et al. (2020) reported emamectin benzoate concentrations of 31.9 ± 9.2 μg/g dry weight at 244 d after injection and 24.7 ± 8.3 μg/g dry weight at 629 d after injection in western white pine, *Pinus monticola* Douglas ex D. Don.

Fettig et al. (2014a) reported that TREE-äge injected at 10 ml/2.54 cm dbh in mid-September (year *X*) provided adequate protection of *P. contorta* from *D. ponderosae* the following field season (year $X + 1$) and that when TREE-äge was combined in solution with the fungicide propiconazole (Alamo®, Syngenta Crop Protection; 10 ml/2.54 cm dbh diluted in 30 ml of distilled water) trees were protected the same year that injections were made. Two field seasons of efficacy are expected (Table 4). Alamo caused a significant reduction in the cross-sectional area of trees with blue stain (Fettig et al. 2014a). Blue stain fungi, which are vectored by *D. ponderosae* and other bark beetles, can have deleterious effects on tree health. Developing larvae and callow adults also obtain vital nutrients by feeding on associated fungal structures (Six and Paine 1998). Some studies have shown that blue stain fungi alone are capable of killing *P. contorta* (e.g., Yamaoka et al. 1995), but others have failed to demonstrate the effect (Strobel and Sugawara 1986). Propiconazole also inhibits the distribution of blue stain fungi in *P. monticola* (Wyka et al.

2016) and *P*. *taeda* (Doccola et al. 2011). Fettig et al. (2014a) found propiconazole residues in *P*. *contorta* phloem shortly (~4.5 wk) after injection in Utah, but significantly higher concentrations were detected 2 mo later.

Spruce beetle. An experimental formulation of emamectin benzoate injected in late August was ineffective for protecting *Pi*. *engelmannii* from *D*. *rufipennis* the following field season in Utah (Grosman et al. 2010b). Subsequently in Utah, Fettig et al. (2017) found that TREE-äge injected at 10 ml/2.54 cm dbh in mid-June at a narrow spacing (7.6 cm apart) was effective for protecting *Pi*. *engelmannii* when applied ~1 yr before being challenge by *D*. *rufipennis* (Table 4). Two field seasons of efficacy were observed. The authors argued that injecting *Pi*. *engelmannii* almost a full year before efficacy is desired and increasing the number of injection points per tree are critical for protecting *Pi*. *engelmannii* from *D*. *rufipennis* in high-elevation forests. Placing injection points as low as possible (i.e., in the root collar and exposed large roots) also appears important.

Fettig et al. (2020) evaluated TREE-äge injected at 10 ml/2.54 cm dbh alone and combined in solution with Alamo (10 ml/2.54 cm dbh diluted in 30 ml of distilled water) for protecting *Pi*. *engelmannii* from *D*. *rufipennis* in Utah. Two injection periods (mid-June and mid-August of the year before trees were first challenged by *D*. *rufipennis*) and distributions of injection points (7.6- and 15.2-cm spacings) were evaluated. Tree mortality was monitored over a 3-yr period. TREE-äge injected in mid-June at a narrow spacing (7.6 cm) was the only effective treatment. Two (but not three) field seasons of protection were observed. The maximum depth of blue stain in the sapwood did not differ among treatments.

Fettig et al. (2022b) evaluated TREE-äge G4 (4.0% a.i.) injected at 7.5 ml/2.54 cm dbh and TREE-äge R10 (9.7% a.i.) injected at 3.2 ml/2.54 cm dbh alone and combined in solution with propiconazole (Propizol®, Arborjet Inc.; 6 ml/2.54 cm dbh mixed with 6 ml/2.54 cm dbh of distilled water) for protecting *Pi*. *engelmannii* from *D. rufipennis* in Wyoming. TREE-äge G4 is a general use systemic insecticide first registered by the EPA in 2015. TREE-äge R10 is a restricted use systemic insecticide first registered by the EPA in 2018. An advantage of TREE-äge R10 is that it is injected at lower volumes, resulting in fast uptake (i.e., a minimum of 3 min/tree using the QUIK-jet AIR system; Fettig et al. 2022b). Treatments were injected mid-July, and *Pi. engelmannii* mortality was determined for the following two field seasons. Both TREE-äge G4 and TREE-äge R10 significantly reduced *Pi. engelmannii* mortality compared with the baited control. However, protection was limited to one field season. Protection was increased to two field seasons by combining TREE-äge G4 and TREE-äge R10 with Propizol. This study highlights the importance of injecting *Pi*. *engelmannii* in late spring or early summer before the year that protection is desired and at narrow spacing (Table 4). In Alaska, TREE-äge G4 and TREE-äge G4 plus Propizol were ineffective for protecting *Pi*. *glauca* from *D*. *rufipennis* (J.E.M. et al. unpubl. data). Thus, caution should be used when extrapolating data on *Pi*. *engelmannii* in the Intermountain West to *Pi*. *glauca* in Alaska.

Engraver beetles. To our knowledge, no studies on the effects of emamectin benzoate on *Ips* species have been conducted in the western United States. In research conducted in Alabama, Mississippi, and Texas, experimental formulations of emamectin benzoate injected at 0.08 g a.i./2.54 cm dbh were effective for reducing attacks by *I*. *calligraphus*, eastern five-spined ips, *Ips grandicollis*

(Eichoff), and the small southern pine engraver, *Ips avulsus* (Eichoff) (Grosman et al. 2009, Grosman and Upton 2006).

Southern pine beetle. To our knowledge, no studies on the effects of emamectin benzoate on *D. frontalis* have been conducted in the western United States. In research conducted in Alabama, experimental formulations of emamectin benzoate injected at 0.08 g a.i./2.54 cm dbh were effective for protecting *P. taeda* from *D. frontalis* (Grosman et al. 2009).

Red turpentine beetle. To our knowledge, no studies on the effects of emamectin benzoate on *D. valens* have been conducted in the western United States.

Abamectin

Abamectin (= avermectin B1) is a natural fermentation product of the soil actinomycete *Streptomyces avermitilis.* Like emamectin benzoate, abamectin acts on insects by interfering with neural and neuromuscular transmission. Abamectin is relatively nontoxic to birds but is highly toxic to fish, aquatic invertebrates, and *A. mellifera* (Bai and Ogbourne 2016). Most formulated products have low toxicity in mammals. Limited research has been conducted on abamectin as a preventative treatment in the western United States. Fettig et al. (2013b) evaluated abamectin (Abacide™ 2Hp, Mauget Inc., Arcadia, CA) injected at 20 ml/2.54 cm dbh alone and combined in solution with tebuconazole (Tebuject™ 16, Mauget Inc.; 6 ml/2.54 cm dbh) for protecting *P. contorta* from *D. ponderosae* in Utah. Treatments were injected in mid-September and evaluated for two field seasons. Both Abacide 2Hp and Abacide 2Hp plus Tebuject 16 were effective for one field season; results from a second field season were inconclusive because of insufficient beetle pressure in the baited control (<60% tree mortality; Shea et al. 1984). Abacide 2Hp plus Tebuject 16 resulted in a significant reduction in the proportion of cross-sectional area with blue stain compared with the baited control but was not significantly different from the effects of Abacide 2Hp alone (Fettig et al. 2013b). In Alaska, Abacide 2 (Mauget Inc.) was ineffective for protecting *Pi. glauca* from *D. rufipennis* (J.E.M. et al. unpubl. data).

Preventative Treatments and Wildfire

In the western United States, a common question from resource managers concerns the direct and indirect effects of wildfire on the efficacy and residual activity of preventative treatments. Given the difficult logistics of executing a study to address this question, the relationship has never been studied. However, research by Fettig et al. (2018) provides some insight on the efficacy and residual activity of 2.0% carbaryl (Sevin SL) as a wildfire burned through their study area at low to moderate severity in mid-summer 2012 after applications of Sevin SL to *P. ponderosa* in fall 2011 and spring 2012. Their hypothesis was that wildfire negatively affects treatment efficacy and residual activity through heating of the environment (which was thought to affect all trees in the experimental population) and burning of carbaryl residues on trees contacted by the wildfire (which affected a known subset of trees in the experimental population based on evidence of bole char). The boiling point of carbaryl is 315°C. However, the authors found no evidence to support this hypothesis. For example, 20 of 29 trees that were treated with Sevin

SL in spring 2012 survived baiting for *D*. *ponderosae* in 2013. The authors also observed no significant differences in measures of fire severity (bole char and crown scorch) between live and dead trees (Fettig et al. 2018). No data are available to allow speculation on the effects of low- to moderate-severity wildfires on tree injections. However, it seems even less likely that the efficacy and residual activity of tree injections would be affected by wildfires because the active ingredients are in the phloem.

Environmental Fate and Risks

Most data on the deposition, toxicity, and environmental fate of insecticides in forests come from aerial applications to control tree defoliators and therefore are of limited applicability here. Hoy and Shea (1981) studied the effects of lindane, chlorpyrifos, and carbaryl on soil arthropod communities in California by spraying normal levels of the insecticides and levels five times greater than would be operationally used to protect conifers from bark beetles. The authors concluded that carbaryl was least disruptive to the soil arthropod community. As might be expected, the highest concentrations of carbaryl were found in the upper 2.54 cm of soil (Hastings et al. 1998). Carbaryl is relatively nontoxic to *Enoclerus lecontei* (Wolcott) (Swezey et al. 1982) and *Enoclerus sphegeus* (F.) (Greene 1983) and less toxic than either lindane or chlorpyrifos to *Temnoscheila chlorodia* (Mannerheim) (Swezey et al. 1982), common predators of bark beetles in the western United States. Werner et al. (1983) measured the effects of 0.25%, 0.5%, 1.0%, and 2.0% chlorpyrifos, fenitrothion, and permethrin on predators and parasites of *D*. *rufipennis* in Alaska and reported that 2.0% permethrin had the least impact.

Werner and Hilgert (1992) monitored permethrin levels in a freshwater stream adjacent to *Pi.* × *lutzii* treated with 0.5% permethrin (Pounce®, FMC Corp.) to prevent *D*. *rufipennis* attack in Alaska. Treatments occurred within 5 m of the stream. Maximum concentrations ranged from 0.05 ± 0.01 ppb 5 h after treatment to 0.14 ± 0.03 ppb 8–11 h after treatment. The mean concentration of permethrin in standing pools near the stream was 0.01 ± 0.01 ppb. Numbers of drifting aquatic invertebrates increased twofold during the treatment and fourfold 3 h after treatment but returned to background levels within 9 h of treatment. Trout fry, periphyton, and benthic invertebrates were unaffected (Werner and Hilgert 1992). Rivera-Dávila et al. (2021) studied the toxicity of bifenthrin, cypermethrin, and deltamethrin on the cladoceran *Alona guttata* Sars and the rotifer *Lecane papuana* (Murray), freshwater species reared in the laboratory. Bifenthrin was the most toxic followed by deltamethrin and cypermethrin.

Surprisingly, there are only two studies published on the amount of drift resulting from bole sprays used to protect conifers from bark beetles. Haverty et al. (1983) used spectrophotofluorometry to analyze ground deposition 1, 3, 5, 8, and 12 m from the bole of *P*. *ponderosa* treated with 1.0% carbaryl (Sevimol) in an arboretum in California. Fettig et al. (2008) used high-performance liquid chromatography (HPLC) to evaluate ground deposition at 7.6, 15.2, 22.9, and 38.1 m from the boles of *Pi*. *contorta* and *Pi*. *engelmannii* treated with 2.0% carbaryl (Sevin SL) during conventional (simulated operational) bole sprays in Utah. Despite substantial differences in methods (i.e., spectrophotofluorometry limits detection of finer

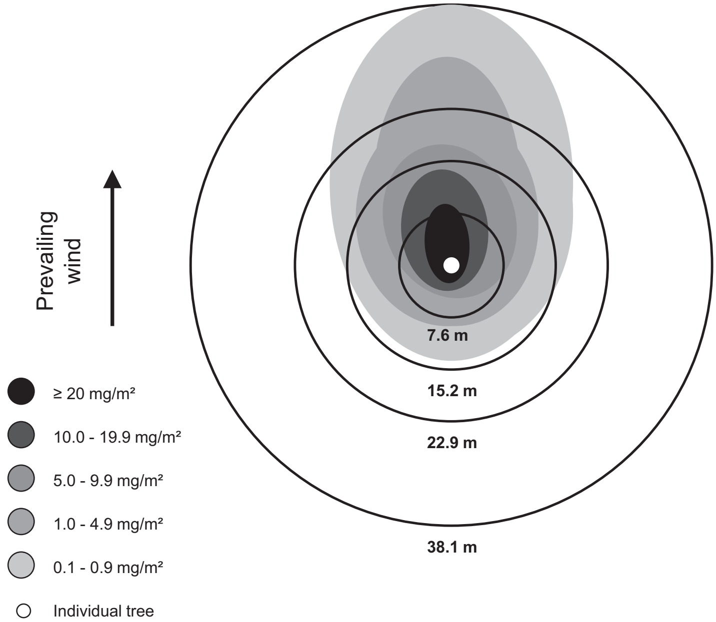

Fig. 4. Average drift following applications of 2.0% (percent active ingredient) carbaryl (Sevin® SL, Bayer CropScience, Research Triangle Park, NC) to protect conifers from bark beetle attack, Uinta-Wasatch-Cache National Forest, Utah. Deposition was detected at 33.8 m on the leeward side of treated trees (mean maximum wind speed, 3.5 km/h) but undetectable less than half of that distance on the windward side. Adapted from Fettig et al. (2008).

particle sizes that are captured with HPLC), these studies yielded comparable results. For example, Fettig et al. (2008) reported application efficiencies (percentage of insecticide applied that is retained on trees) of 80.9–87.2%, and Haverty et al. (1983) reported values of $>$80%. Fettig et al. (2008) found no significant difference in the amount of drift occurring between *P*. *contorta* and *Pi*. *engelmannii* at any distance from the tree bole despite differences in application rates, whereas Haverty et al. (1983) reported that drift was similar between two applications at 276 kPa and 2,930 kPa. A noticeable difference between these studies is that Fettig et al. (2008) detected higher levels of ground deposition further from the tree bole, which is expected given their use of HPLC.

Fettig et al. (2008) reported mean deposition values ranging from 0.04 $\pm$ 0.02 mg carbaryl/m^2 at 38.1 m to 13.30 $\pm$ 2.54 mg carbaryl/m^2 at 7.6 m. Approximately 97% of total spray deposition occurred within 15.2 m of the tree bole (Fig. 4). To evaluate the potential risk to aquatic environments, the authors converted mean deposition to mean concentration assuming a water depth of 0.3 m selected to represent the average size of lotic systems adjacent to many recreational sites where bole sprays are applied. No adjustments were made for the degradation of carbaryl by hydrolysis, which is rapid in streams, or for dilution by natural flow.

Comparisons were made with published toxicology data for select aquatic organisms. No-spray buffers of 7.6 m are sufficient to protect freshwater fish, amphibians, crustaceans, bivalves, and most aquatic insects. No-spray buffers >22.9 m are sufficient to protect the most sensitive aquatic insects, including Plecoptera and Ephemeroptera (Beyers et al. 1995). Data provided by Fettig et al. (2008) still serve as the standard for prescribing no-spray buffers in the western United States. An extension bulletin is available to assist applicators and resource managers with determining no-spray buffers (Fettig et al. 2014b).

Tree injections represent essentially closed systems, with little or no contamination occurring outside of the tree during treatment (Table 2). However, following injections residues have been detected in foliage, which could pose a risk to decomposers and other soil fauna. Takai et al. (2004) reported that emamectin benzoate was not detected in the roots of Japanese black pine, *Pinus thunbergii* Palatore, and Japanese red pine, *Pinus densiflora* Siebold & Zuccarini, injected with emamectin benzoate or in the surrounding soil but was present at 0.011–0.025 μg/g in freshly fallen needles. Levels gradually declined to below detectable thresholds after 2 mo. Ouyang et al. (2023) found that the richness and diversity of soil arthropods were unaffected by injections of emamectin benzoate used to control pine wood nematode, *Bursapherenchus xylophilus* Steiner & Buhrer, in Masson's pine, *Pinus massoniana* Lambert, in China. Burkhard et al. (2015) injected emamectin benzoate into horse chestnut, *Aesculus hippocastanum* L., in Switzerland and reported that the half-life in decomposing leaves was 20 d in compost piles, 94 d in leaves immersed in water, and 212 d in leaves left on the ground. No emamectin benzoate was found in water containing decomposing leaves, which is not surprising given the low water solubility of emamectin benzoate (24 mg/L). The authors concluded that emamectin benzoate present in abscised leaves from *A. hippocastanum* poses no threat to nontarget organisms in soil or water. To our knowledge, no studies have been conducted to assess these types of relationships following preventative treatments with systemic insecticides in the western United States.

Pine Nuts

Pine nuts are harvested in natural stands and plantations for human consumption in many parts of the world (Sharashkin and Gold 2004). To our knowledge, no studies have been conducted to assess the effects of preventative treatments on nuts harvested from pinyon pines in the western United States. In Spain, recurrent droughts and the western conifer seed bug, *Leptoglossus occidentalis* Heidemann, have severely impacted stone pine, *Pinus pinea* L., nut production in recent years, and deltamethrin is being evaluated for its effect on improving yields (Bellot et al. 2023). Sprays were applied in May after peak adult emergence and again at the end of July. Deltamethrin concentrations in nuts were lower than those in needles, and residues in nuts were well below the legal threshold. In Texas, Grosman et al. (2010a) injected TREE-äge at 10 ml/2.54 cm dbh into young cherrybark oaks, *Quercus pagoda* Rafinesque, and reported moderate levels (~150 ppb) of emamectin benzoate in leaves but none in acorns. When TREE-äge was injected into black walnut, *Juglans nigra* L., detectable levels of emamectin benzoate were found in the xylem (1,379 ppb) and phloem (23 ppb) but not in the nuts (D.M.G. unpubl. data).

Smoke from Treated Trees

A common issue for resource managers concerns health risks from firewood collected from trees treated with insecticides. Peterson and Costello (2013) sampled bark from *P. ponderosa* and *P. contorta* treated with 2.0% carbaryl (Sevin SL) in Colorado 1 d after application and at 4-mo intervals for 1 yr. The amount of carbaryl on the bark was relatively stable throughout the study period. Ground bark samples (0.5 g) were treated with 60 μl of Sevin SL solution and burned at 500°C for 5 min in the laboratory. At 5 mo, mean values ranged from ~5 ppm (*P. ponderosa*) to ~24 ppm (*P. contorta*) (Peterson and Costello 2013). The authors suggested that because fireplaces operate at >500°C, less carbaryl would be recovered from smoke in fireplaces than in their study and that carbaryl would be absent from smoke produced from much hotter fires. To our knowledge, no other studies have been conducted to assess these relationships for other common preventative treatments in the western United States.

Conclusions

Preventative applications of insecticides are a viable option for protecting individual conifers from bark beetles in the western United States. Bole sprays of bifenthrin, carbaryl, and permethrin are most common, and several products are effective when properly applied in accordance with the label. Recent advances in tree injection, especially formulations of emamectin benzoate, offer a viable alternative to bole sprays, and there are advantages and disadvantages to each method (Table 3). The residual activity of preventative treatments differs with active ingredient, bark beetle species, tree species, abiotic factors, and other factors, but generally one to three field seasons of protection can be expected with a single application (Tables 2, 3). These treatments pose little threat to the environment (Fig. 4), and few negative impacts have been observed. We encourage forest health professionals and other resource managers to use this review and other published reports to make informed, judicious decisions concerning the use of preventative treatments. An extension bulletin is available that provides recommendations and a decision flow chart for hiring pest control companies and applicators (Taravati et al. 2023). Additional technical assistance can be obtained from Forest Health Protection (USDA Forest Service) entomologists, state forest entomologists, and county extension agents.

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