Spray Deposition from Ground-based Applications of Carbaryl to Protect Individual Trees from Bark Beetle Attack

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Bark beetles (Coleoptera: Curculionidae, Scolytinae) are recognized as the most important tree mortality agent in western coniferous forests. A common method of protecting trees from bark beetle attack is to saturate the tree bole with carbaryl (1-naphthyl methylcarbamate) using a hydraulic sprayer. In this study, we evaluate the amount of carbaryl drift (ground deposition) occurring at four distances from the tree bole (7.6, 15.2, 22.9, and 38.1 m) during conventional spray applications for protecting individual lodgepole pine (*Pinus contorta* Dougl. ex Loud.) from mountain pine beetle (*Dendroctonus ponderosae* Hopkins) attack and Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) from spruce beetle (*D. rufipennis* [Kirby]) attack. Mean deposition (carbaryl + α-naphthol) did not differ significantly among treatments (nozzle orifices) at any distance from the tree bole. Values ranged from 0.04 ± 0.02 mg carbaryl m^{-2} at 38.1 m to 13.30 ± 2.54 mg carbaryl m^{-2} at 7.6 m. Overall, distance from the tree bole significantly affected the amount of deposition. Deposition was greatest 7.6 m from the tree bole and quickly declined as distance from the tree bole increased. Approximately 97% of total spray deposition occurred within 15.2 m of the tree bole. Application efficiency (i.e., percentage of insecticide applied that is retained on trees) ranged from 80.9 to 87.2%. Based on review of the literature, this amount of drift poses little threat to adjacent aquatic environments. No-spray buffers of 7.6 m should be sufficient to protect freshwater fish, amphibians, crustaceans, bivalves, and most aquatic insects. Buffers >22.9 m appear sufficient to protect the most sensitive aquatic insects (Plecoptera).

Bark beetles (Coleoptera: Curculionidae, Scolytinae) are recognized as the most important tree mortality agent in western coniferous forests. The last decade has seen elevated levels of tree mortality in spruce (*Picea* spp.) forests of south-central Alaska and the Rocky Mountains (Holsten et al., 1999; Wittwer, 2000; DeRose and Long, 2007), lodgepole pine (*Pinus contorta* Dougl. ex Loud.) forests of western Canada and the Rocky Mountains (Wilent, 2005; Struck, 2006), pinyon-juniper (*Pinus-Juniperus* spp.) woodlands of the southwestern USA (Shaw et al., 2005), and ponderosa pine (*P. ponderosa* Dougl. ex Laws.) forests of Arizona (USDA Forest Service, 2004) and California (USDA Forest Service, 2002). Bark beetle epidemics affect timber and fiber production, water quality and quantity, fish and wildlife populations, recreation, grazing capacity, real estate values, biodiversity, cultural resources, and other resources. Furthermore, tree losses in recreational, residential, or administrative sites generally result in costs associated with hazardous tree inspections and removal (Johnson, 1981); litigation (Johnson, 1981); reduced shade, screening, and aesthetics (Helm and Johnson, 1995; Haverty et al., 1998); and reductions in property values (McGregor and Cole, 1985). Techniques for managing bark beetle infestations are limited to tree removals (thinning) that reduce stand density and presumably host susceptibility (Fettig et al., 2007) and the use of insecticides (Haverty et al., 1998; Hastings et al., 2001; Fettig et al., 2006a,b) and semiochemicals (i.e., chemicals produced by one organism that elicit a response, usually behavioral, in another organism) for specific bark beetle-host species complexes (Goyer et al., 1998).

Mountain pine beetle (*Dendroctonus ponderosae* Hopkins) is the most destructive bark beetle in western North America (Furniss and Carolin, 1977). Since 2001, more than 350,000 ha of lodgepole pine forest have been infested in the western USA (Matthews et al., 2005). Spruce beetle (*D. rufipennis* [Kirby]) is the most significant mortality agent of mature spruce (Holsten et al., 1999). From 1990 to 2005, large amounts of Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) mortality were attributed to spruce beetle in the Rocky

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Abbreviations: a.i., active ingredient; dbh, diameter at breast height (1.37 m); HPLC, high-performance liquid chromatography; LC_{50}, median lethal concentration that kills 50% of test organisms; SDI, stand density index.

Mountains (Matthews et al., 2005). In the western USA, these and several other bark beetle species are prevented from successfully attacking individual trees by applications of insecticides. The most common method is to saturate the tree bole with carbaryl (1-naphthyl methylcarbamate) or permethrin (3-[phenoxyphenyl]methyl [±]-*cis*,trans-3-[2,2-dichloroethenyl]-2,2-dimethylcyclopropane-carboxylate) using a hydraulic sprayer at high pressure (≥2068 kPa [300 psi]). Carbaryl is a carbamate insecticide registered for control of a wide range of insects on more than 100 agricultural crops and non-crop uses. Hastings et al. (2001) provide an excellent review of the use of carbaryl in coniferous forests of North America.

Most data on the deposition, toxicity, and environmental fate of carbaryl in forest ecosystems come from aerial applications to control tree defoliators (Murphy and Croft, 1990; Torgenson et al., 1995; Hastings et al., 2001). Hoy and Shea (1981) studied the effects of lindane (1,2,3,4,5,6-hexachlorocyclohexane), chlorpyrifos (*O*,*O*-diethyl *O*-[3,5,6-trichloro-2-pyridyl] phosphorothioate), and carbaryl on a California pine forest soil arthropod community by spraying normal levels of insecticide and levels five times greater than would be operationally used to protect individual trees from bark beetle attack (i.e., commonly referred to as "single tree protection treatments"). Springtails (Collembola) were quite sensitive to carbaryl, but lindane and chlorpyrifos were even more toxic. The authors concluded that carbaryl was the least disruptive to the soil arthropod community (Hoy and Shea, 1981). Swezey et al. (1982) evaluated the non-target effects of topically applied lindane, chlorpyrifos, and carbaryl on two common bark beetle predators indigenous to the western USA. Carbaryl was relatively nontoxic to *Enoclerus lecontei* (Wolcott) (Coleoptera: Cleridae) and less toxic than lindane or chlorpyrifos to *Temnochila chlorodia* (Mannerheim) (Coleoptera: Trogositidae). Fettig et al. (2006a) concluded that in many respects carbaryl is one of the most effective, economically viable, and ecologically compatible insecticides available for protecting individual trees from bark beetle attack in the western USA. Carbaryl is not effective for preventing southern pine beetle (*D. frontalis* Zimmermann) attack (Berisford et al., 1981), which later was linked to tolerance in that beetle associated with an efficient conversion of carbaryl into metabolites and a rapid rate of excretion (Zhong et al., 1995).

In the western USA, forest health specialists typically specify no-spray buffers of 15.2 to 30.5 m from certain attributes, usually streams and lakes, in contracts or prescriptions for single tree protection treatments (A.S. Munson, unpublished data). To our knowledge, only one study has been published on the amount of drift resulting from such treatments. In that study, ground deposition of carbaryl was analyzed up to 12 m from the tree bole using spectrophotofluorometry (Haverty et al., 1983). The objectives of our study were (i) to evaluate the amount of drift (ground deposition) occurring at four distances from the tree bole (7.6, 15.2, 22.9, and 38.1 m) during carbaryl applications for protecting individual lodgepole pine from mountain pine beetle attack and Engelmann spruce from spruce beetle attack and (ii) to estimate the threat that drift resulting from these treatments poses to select taxa in nearby aquatic systems.

Table 1. Nozzle orifice sizes used during ground-based applications of carbaryl to protect individual lodgepole pine and Engelmann spruce from bark beetle attack, Wasatch-Cache National Forest, Utah, 2006.

Orifice size†	Diameter of aperture	Volume (2068 kPa [300 psi])	Volume (2758 kPa [400 psi])
	cm	L min^{-1}	
#8	0.318	19.7	22.7
#10	0.396	30.7	34.8
#12	0.475	45.4	52.6

† Product No. 11-854-00, Mighty Mag Tree Spray Gun; GNC Industries, Inc., Pocahontas, AR.

Materials and Methods

Study Area and Treatments

This study was conducted on the Evanston Ranger District, Wasatch-Cache National Forest, Utah (Tree 1 = 40.84° N, 110.85° W; Tree 60 = 40.85° N, 110.93° W; 2682–2865 m elevation), 2006. Carbaryl was applied at the maximum label rate (2.0% active ingredient [a.i.] in water) (Sevin SL; Bayer Environmental Science, Montvale, NJ; U.S. Environmental Protection Agency Reg. No. 432-1227) to 30 lodgepole pine and 30 Engelmann spruce using a trailer-mounted hydraulic sprayer (Model No. 0021-F200-1511; GNC Industries, Inc., Pocahontas, AR) comprised of a 757-L fiberglass tank with a P15 hydraulic pump powered by a gasoline motor and equipped with a Mighty Mag Tree Spray Gun (Product No. 11-854-00; GNC Industries, Inc.) (Table 1). This sprayer allowed treatment of the tree bole, until runoff, to a height of approximately 12.2 m, which is typical of single tree protection treatments. Sprays were applied at 2241 kPa (325 psi) for lodgepole pine (28.5 ± 1.5 cm diameter at breast height [dbh; 1.37 m]; mean ± SEM) and 2758 kPa (400 psi) for Engelmann spruce (41.0 ± 2.0 cm dbh). The pressure for Engelmann spruce was higher to facilitate the treatment of taller trees as is commonly prescribed. Treatments (2 tree species × 3 nozzle orifice sizes × 10 replicates/orifice size; Table 1) were applied 19 through 22 June 2006 between 0545 and 1145 MDT by a single certified pesticide applicator (R.R.B.). Each tree was treated from four separate faces to ensure complete coverage of the tree bole. Maximum air temperature, relative humidity, wind speed, and wind direction were recorded at 2 m in height during treatment of each tree (Kestrel 3000; Forestry Suppliers, Inc., Jackson, MS) (Table 2). Measures of stand structure and composition were collected using conventional methods in one 0.081-ha circular plot (radius = 16.1 m) surrounding each experimental tree (Table 2).

Drift Collection

Spray drift was sampled on 9-cm diameter glass microfiber filter discs (Whatman 934-AH, 1.5 µm pore size; Cole-Parmer, Vernon Hills, IL) placed at four distances from the tree bole (7.6, 15.2, 22.9, and 38.1 m) and at eight bearings at each distance (0, 45, 90, 135, 180, 225, 270, and 315°). Filters were stored in 10-cm diameter sterile polystyrene Petri dishes (Cole-Parmer, Vernon Hills, IL) before use, laid flat on the forest floor, and only opened to the environment during spray applications. At the beginning of each day, quality assurance samples (control filters) were exposed in adjacent untreated areas to monitor for possible

Table 2. Stand and weather conditions during ground-based carbaryl sprays to protect individual lodgepole pine and Engelmann spruce from bark beetle attack, Wasatch-Cache National Forest, Utah, 2006.

Tree species†	Dbh‡	Orifice no.	Basal area	Trees ha^{-1}	SDI‡	Crown cover§	Temp.	RH	Wind speed	Direction¶
	cm		$m^2\ ha^{-1}$			%	°C	%	$km\ h^{-1}$	degrees
LP	26.9	10	9.9	284	85.1	40	14.2	30.7	3.7	220
LP	23.9	12	16.8	643	153.3	40	18.9	31.4	4.5	245
LP	27.2	10	16.9	581	150.6	40	17.7	30.0	4.7	213
LP	23.1	8	17.2	655	157.0	40	18.3	25.9	3.9	218
LP	29.0	12	15.3	519	136.6	60	20.3	22.5	10.6	175
LP	19.3	12	41.3	1038	346.3	80	21.3	21.3	12.9	185
LP	31.8	8	26.2	791	227.7	80	22.7	20.5	9.3	130
LP	28.4	10	33.7	692	272.0	80	21.1	24.1	23.7	213
LP	23.4	8	29.9	988	264.8	60	4.4	48.8	0.0	–
LP	24.4	12	40.3	1161	347.6	80	6.8	65.6	0.0	–
LP	20.3	12	16.2	494	141.2	60	8.7	60.1	0.0	–
LP	20.8	8	42.6	1557	385.3	100	10.7	56.0	0.0	–
LP	20.3	10	38.7	1137	334.9	100	9.8	57.0	0.0	–
LP	17.8	8	31.0	914	268.8	80	9.8	56.5	0.0	–
LP	23.1	12	28.4	865	247.4	60	7.8	67.8	0.0	–
LP	37.6	8	7.5	124	57.8	20	6.3	76.0	0.0	–
LP	29.0	10	22.4	470	181.5	60	10.1	60.2	0.0	–
LP	19.6	10	20.0	395	160.2	80	13.5	57.6	0.0	–
ES	40.4	8	35.5	643	279.1	40	12.5	59.4	1.3	150
LP	40.6	8	24.1	544	197.8	20	18.8	40.6	5.8	30
LP	39.6	12	3.0	25	20.4	10	18.5	44.3	11.7	295
LP	48.5	12	28.4	717	238.7	80	24.9	40.8	12.4	220
LP	34.3	10	45.5	1087	378.2	80	25.3	23.3	12.2	200
LP	46.5	10	4.8	99	38.9	20	24.6	32.3	15.0	200
LP	29.0	8	36.6	766	296.6	80	1.3	56.0	0.0	–
LP	24.6	12	42.3	1211	364.6	80	0.3	57.9	0.0	–
LP	22.9	10	47.4	1927	437.4	100	−0.2	62.1	0.0	–
LP	33.5	12	27.3	1013	247.6	100	1.3	61.3	0.0	–
LP	29.0	8	8.2	198	68.3	20	1.4	57.9	0.0	–
LP	22.4	8	34.8	568	268.5	40	1.3	58.9	0.0	–
LP	31.2	10	35.7	692	284.7	60	0.0	55.4	0.0	–
ES	40.6	12	55.0	791	413.5	40	0.3	56.2	0.0	–
ES	21.1	8	44.4	815	350.2	60	1.4	61.2	0.0	–
ES	26.2	8	37.8	544	284.1	60	3.0	63.2	0.0	–
ES	50.0	8	50.7	1087	412.6	60	5.1	71.7	0.0	–
ES	41.7	8	27.6	741	235.0	80	6.1	66.4	0.0	–
ES	25.9	12	24.0	618	202.2	60	12.1	44.3	0.0	–
ES	33.3	8	56.7	1211	460.7	20	14.4	30.0	0.0	–
ES	35.6	10	37.9	815	308.5	60	13.0	40.5	2.1	115
ES	36.6	12	33.7	568	261.4	20	15.6	33.3	1.8	30
ES	51.8	12	22.6	593	191.7	60	16.0	32.1	7.4	150
ES	29.2	8	32.2	914	277.2	60	19.6	22.2	4.5	0
ES	30.5	10	28.0	395	209.8	60	19.4	28.9	7.2	18
ES	46.0	12	37.1	643	289.3	60	17.8	25.5	2.9	340
ES	65.5	10	10.0	74	65.8	20	18.8	25.9	10.5	90
ES	34.0	10	54.0	667	393.8	80	18.4	24.2	2.4	200
ES	53.1	8	41.0	494	297.9	40	22.5	25.1	14.3	60
ES	50.0	10	30.9	371	223.9	80	6.3	34.2	0.0	–
ES	43.9	10	22.1	371	171.5	20	3.9	45.4	0.0	–
ES	33.5	10	26.6	494	210.1	80	3.5	44.3	0.0	–
ES	32.3	10	20.2	445	165.5	60	5.0	54.3	0.0	–
ES	30.2	10	38.7	1384	348.0	60	4.7	51.9	0.0	–
ES	39.6	12	15.2	568	138.0	60	4.8	53.7	4.0	230
ES	41.9	12	35.9	939	303.9	60	4.4	59.3	2.3	340
ES	41.7	12	29.2	494	226.4	60	6.6	59.7	1.9	322
ES	51.3	12	69.7	865	508.8	40	13.0	47.7	0.0	–
ES	49.5	12	26.9	420	205.3	20	16.2	33.0	0.0	–
ES	57.9	8	48.2	395	324.3	80	13.1	60.1	4.2	360
ES	52.6	8	43.1	1211	369.8	80	15.6	50.4	10.0	230
ES	54.1	10	85.4	1359	655.2	60	16.7	48.6	7.6	230

† ES, Engelmann spruce; LP, lodgepole pine.

‡ Dbh, diameter at breast height (1.37 m in height); SDI, stand density index. SDI is a measure of avg. stand density based on the relationship between no. of trees and tree size (quadratic mean diameter). All stand conditions based on data collected in one 0.081-ha circular plot (radius = 16.1 m) surrounding each experimental tree.

§ Based on measurement with densitometer (GRS Vertical Densitometer, Geographic Resource Solutions, Arcata, CA) at plot center and at four cardinal directions 16.1 m from plot center.

¶ Indicates the direction from which the wind is blowing. All weather data report maximum values recorded at 2 m in height during applications.

field contamination. All individual filters and Petri dishes (n = 32 per tree) were collected after treatment, closed, and sealed with Parafilm M (Pechiney Plastic Packaging, Inc., Neenah, WI). Each Petri dish was individually labeled and stored in coolers containing blue ice. Coolers were shipped daily via overnight carrier to the Agricultural and Environmental Services Laboratory at The University of Georgia for further processing. Temperatures were monitored during shipment, and quality assurance samples were placed in each cooler to monitor for contamination during transport.

Extraction and Quantification of Carbaryl

All samples (N = 1920 + quality assurance samples) arrived at the Agricultural and Environmental Services Laboratory within 18 h of shipping and at suitable temperatures (<6°C, all cases). No evidence of contamination during shipment was found. Samples were logged in and stored at −20 ± 4°C until further analysis. Each 9-cm diameter glass microfiber filter disc was transferred to a 15-mL glass culture tube, and 5 mL of mobile phase (acetonitrile:water:methanol; high-performance liquid chromatography [HPLC] grade, 99.8% pure]; 40:40:20, v/v/v) was added. The samples were vortexed and then sonicated for 30 min in an ultrasonic water bath. An aliquot was withdrawn, filtered through a 0.45-µm syringe filter (Whatman Puradisc 25PP, polypropylene filter and housing, 25-mm diameter; Cole-Parmer, Vernon Hills, IL), and transferred to an auto sampler vial for HPLC analysis. Samples were analyzed on a Hewlett-Packard Model 1100 HPLC (Hewlett-Packard Company, Palo Alto, CA) equipped with an auto sampler, UV detector (wavelength: 230 nm), and a reverse-phase, HPLC-LC-18, 5 cm × 4.6 mm, 5-µm sphere size column (Supelco Column 7954905) operated at room

temperature. Carbaryl and α-naphthol standards were purchased from AccuStandard (Cat # P-083S; AccuStandard Inc., New Haven, CT) and Sigma Aldrich (Cat # N-1000; Sigma Aldrich, St. Louis, MO), respectively.

Carbaryl and α-naphthol concentrations were calculated from the regression equation generated by a five-point regression curve in WindowChem's Standard Curves program (ChemSW, Fairfield, CA). A reagent blank and mid-range standard were included with each analytical batch of samples. Duplicate analysis was conducted for every 20 samples or per analytical batch of fewer than 20 samples. Analytical precision was measured as the percent difference between each set of duplicates. Accuracy of the analytical procedure was measured as percent recovery of blanks that had been fortified at 2 to 5 times the method detection limit of 1 µg per disc. Carbaryl recovery was 78 to 93% for samples fortified at 2 µg per disc and 50 to 145% for samples fortified at 5 µg per disc. If samples were allowed to sit in the auto-sampler for an extended period of time (e.g., due to instrument problems), photolysis of carbaryl to α-naphthol was observed and resulted in recoveries of <80%. To correct for breakdown, total carbaryl (carbaryl + α-naphthol) is reported herein.

Experimental Design and Analyses

The experimental design was completely randomized with six treatments (tree species × orifice sizes) and 10 replicates per treatment. The primary variable of interest was the amount of carbaryl deposited at each of four distances from the tree bole. Early analyses indicated there were no significant differences between tree species (df = 1, 58; $P > 0.55$, all cases), and therefore data were pooled at this level for subsequent analyses. We performed a one-way ANOVA using $\alpha = 0.05$ (df = 2, 57) (JMP Version 3.2.6, SAS Institute Inc., Cary, NC; SigmaStat Version 2.0, SPSS Inc., Chicago, IL). Tests of normality were performed, and appropriate transformations were used (ln [x + 1] deposition; arcsine square root [percentages]; Sokal and Rohlf, 1995) if data deviated significantly from a normal distribution. If a significant treatment effect was detected, Tukey's multiple comparison test (Tukey's HSD) was used for separation of treatment means. Relationships between stand and weather variables and deposition were analyzed using Pearson's correlation coefficient with transformed data (SigmaStat Version 2.0; SPSS Inc., Chicago, IL) and, in some cases, regression analyses. Application efficiency, defined as 1 minus the ratio of ground deposition to the total application rate, was calculated for each orifice size based on mean application rates per tree.

A simple diagram representing mean deposition values (mg carbaryl m^{-2}) for each of 32 sample points was developed in Powerpoint (Microsoft Corp., Redmond, WA). The direction of prevailing drift, based on the maximum deposition values recorded at 22.9 m, was standardized to 0° for each tree. Deposition values were placed into six classes (0.1–0.9, 1.0–4.9, 5.0–9.9, 10–19.9, and ≥20.0 mg carbaryl m^{-2}), and distributions were graphically displayed. The placement of classes between adjacent sample points was based on a linear relationship between deposition and distance between sample points.

To evaluate the potential threat of single tree protection treatments to aquatic environments, mean deposition (mg carbaryl m^{-2}) was converted to mean concentration (mg carbaryl L^{-1}), assuming a water depth of 0.3048 m by dividing mean deposition by 304.8. This depth was arbitrarily selected to represent the average size of lotic systems, primarily small mountain streams, adjacent to many recreation sites (e.g., campgrounds) where single tree protection treatments are commonly implemented. It is probably an overly conservative estimate for lentic systems, which are generally much deeper. No adjustments were made for the degradation of carbaryl by hydrolysis, which is rapid in lotic systems (Stanley and Trial, 1980; Beyers et al., 1995), or dissolution by natural flow. Comparisons were made with published toxicology data available for select taxa.

Results and Discussion

On average, 29.5 L of insecticide spray (insecticide + water) was applied to each tree, which is equivalent to <1 min of spraying with a #10 orifice at 2068 kPa (300 psi) (Table 1). Slightly higher quantities were applied to Engelmann spruce than lodgepole pine (30.7 versus 28.3 L, respectively) because Engelmann spruce trees were larger and treated at higher pressure. Our application rates are higher than those reported elsewhere, which is likely attributed to use of a larger orifice (#12) than is typically used in single tree protection treatments. For example, Fettig et al. (2006b) applied 17.8 and 19.5 L to individual ponderosa pine (39.9 cm mean dbh) and lodgepole pine (27.7 cm mean dbh), respectively, using a #8 orifice at 2068 kPa (300 psi). DeGomez et al. (2006) applied about 26 L of insecticide spray to individual ponderosa pines (26.5 cm mean dbh). We found no significant difference in the amount of drift occurring between lodgepole pine and Engelmann spruce at any distance from the tree bole ($P > 0.05$, all cases) despite differences in application rate and pressure. Haverty et al. (1983) reported drift was similar between two ground-based treatments applied at 276 kPa (40 psi) and 2930 kPa (425 psi) to individual ponderosa pine.

Mean stand density was 31.8 ± 2.0 m^2 ha^{-1}, with lodgepole pine and quaking aspen (*Populus tremuloides* Michx.) predominant at lower elevations, and Engelmann spruce, subalpine fir (*Abies lasiocarpa* [Hook.] Nutt) and lodgepole pine predominate at higher elevations. The mean number of trees per ha was 718.0 ± 48.0. Mean crown cover was 58.2 ± 3.1%. Temperatures averaged 11.5 ± 1.0°C and ranged from −0.2 to 25.3°C. Mean relative humidity was 45.9 ± 2.0%. Maximum wind speed averaged 3.6 ± 0.7 km h^{-1} and ranged from undetectable (52% of applications) to 23.7 km h^{-1} (Table 2). Generally, prescriptions for single tree protection treatments require maximum wind speeds to be <16.1 km h^{-1}. This value was exceeded once during our study (Table 2).

The application efficiency of orifices #8, #10, and #12 were 87.2, 82.1, and 80.9%, respectively. This agrees with a previous report indicating that >80% of the insecticide applied during single tree protection treatments stayed on the tree (Haverty et al., 1983). The amount of carbaryl (carbaryl + α-naphthol) deposited on the ground (mg m^{-2}) was not significantly different among orifice sizes at any distance from the tree bole ($P > 0.06$, all cases; Table 3). A trend existed at 7.6 m in that lower levels of deposition

Table 3. Mean deposition (±SEM) and mean percentage of total deposition (±SEM) at four distances from the bole of individual lodgepole pine and Engelmann spruce treated with 2.0% active ingredient carbaryl for protection against bark beetle attack, Wasatch-Cache National Forest, Utah, 2006.

		7.6 m		15.2 m		22.9 m		38.1 m	
Orifice size	*n*	Mean deposition†	% of total deposition‡	Mean deposition†	% of total deposition‡	Mean deposition†	% of total deposition‡	Mean deposition†	% of total deposition‡
#8	20	7.39 ± 1.61 a	84.4 ± 2.7 a	1.16 ± 0.41 a	12.0 ± 2.5 a	0.16 ± 0.05 a	2.1 ± 0.5 a	0.04 ± 0.02 a	1.5 ± 1.1 a
#10	20	9.84 ± 1.49 a	87.0 ± 2.3 a	1.42 ± 0.58 a	9.4 ± 2.1 a	0.33 ± 0.16 a	3.0 ± 1.3 a	0.04 ± 0.01 a	0.6 ± 0.2 a
#12	20	13.30 ± 2.54 a	90.6 ± 1.6 a	1.07 ± 0.30 a	7.3 ± 1.3 a	0.29 ± 0.11 a	1.8 ± 0.5 a	0.04 ± 0.02 a	0.3 ± 0.1 a
		$F_{2,57}$ = 3.28; P = 0.06	$F_{2,57}$ = 1.45; P = 0.24	$F_{2,57}$ = 0.37; P = 0.69	$F_{2,57}$ = 1.07; P = 0.35	$F_{2,57}$ = 0.88; P = 0.42	$F_{2,57}$ = 0.53; P = 0.59	$F_{2,57}$ = 1.87; P = 0.16	$F_{2,57}$ = 0.55; P = 0.58

† Mean ± SEM deposition (mg carbaryl m^{-2}) collected on eight filters (9-cm diameter) per tree at each distance for each of 20 trees per orifice size. Means followed by the same letter within column are not significantly different (P > 0.05; Tukey's HSD).

‡ Mean percentage (±SEM) of total deposition (mg carbaryl m^{-2}) at each distance. Means followed by the same letter within column are not significantly different (P > 0.05; Tukey's HSD).

occurred with smaller orifices (Table 3), although the effect was not statistically significant ($F_{2,57}$ = 3.28; P = 0.06). Mean deposition ranged from 0.4 ± 0.02 mg carbaryl m^{-2} (#8 and #12 at 38.1 m) to 13.30 ± 2.54 mg carbaryl m^{-2} (#12 at 7.6 m). Mast et al. (2007) estimated annual deposition of carbaryl in remote areas of Rocky Mountain National Park, Colorado, at 0.0099 mg m^{-2}. This annual "background" level is approximately four times less than occurred at 38.1 m during our treatments. Distance from the tree bole significantly affected the amount of deposition ($F_{3,236}$ = 181.1; P < 0.001; Fig. 1A). Deposition was greatest 7.6 m from the tree bole and quickly declined thereafter (Fig. 1A). No significant difference was found between 22.9 and 38.1 m (Fig. 1A). Approximately 97% of total deposition occurred within 15.2 m of the tree bole (Fig. 1B). We found no significant differences among orifices in the percentage of total deposition collected at each distance from the tree bole (Table 3). Mean percentage of total deposition ranged from 0.3 ± 0.1% (#12 at 38.1 m) to 90.6 ± 1.6% (#12 at 7.6 m).

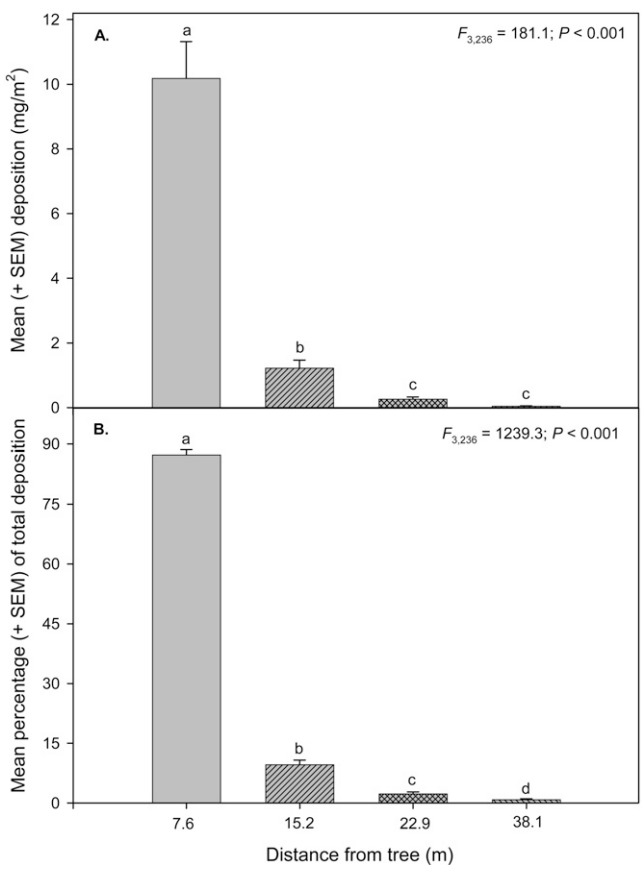

Fig. 1. Mean deposition (+ SEM) of carbaryl (mg m^{-2}) (A) and mean percentage (+ SEM) of total deposition (B) at four distances from the tree bole after ground-based sprays to protect individual lodgepole pine and Engelmann spruce from bark beetle attack, Wasatch-Cache National Forest, Utah, 2006. Means followed by the same letter are not significantly different (Tukey's HSD; P > 0.05).

Haverty et al. (1983) conducted a study to determine the amount of ground deposition at 1, 3, 5, 8, and 12 m from the bole of individual ponderosa pines growing in an arboretum. Trees were treated with 1.0% a.i. carbaryl (Sevimol) with a dye added for assessing deposition with a spectrophotofluorometer. Deposition was greatest at 1 m from the tree bole and nearly undetectable at 12 m. Forty-five percent of total deposition fell within 2 m of the tree bole. The authors reported that 144 mg m^{-2} (equal to 14.4 μg cm^{-2} as originally reported) of carbaryl were deposited 3 m from the bole. Berisford et al. (1991) reported that 184 mg m^{-2} (equal to 1.837 kg ha^{-1} as originally reported) of chlorpyrifos (2.0% a.i. Dursban) was deposited within 3.65 m of shortleaf pines (*P. echinata* Miller) treated in a seed orchard in North Carolina.

Haverty et al. (1983) reported 3 mg carbaryl m^{-2} (equal to 0.3 μg cm^{-2} as originally reported) at 8 m from the tree bole, which is about 2.5 to 4.4 times lower than reported in our study at 7.6 m (Table 3). Although there are likely to be differences based on weather, stand structure, and tree composition, we believe that much of the discrepancy between these two studies can be explained by differences in the materials and methods used. A higher concentration of carbaryl was used in our study (i.e., 2.0 versus 1.0% a.i.), but one that is commonly used for single tree protection treatments in the western USA (Hastings et al., 2001; Fettig et al., 2006a,b). There is evidence that lower rates are suitable for tree protection. For example, Shea and McGregor (1987) evaluated the efficacy of 0.5, 1.0, and 2.0% carbaryl (Sevimol and Sevin XLR) and found that all concentrations and formulations were effective for protecting lodgepole pine from mountain pine beetle attack for 1 yr. The 1.0 and 2.0% rates were efficacious for 2 yr, providing ≥80 and ≥90% tree survival, respectively. Johnson (1996) reported that applications of 1.0 and 2.0% carbaryl (Sevimol) were effective for protecting Engelmann spruce for 2 yr in Utah. Additionally, Haverty et al. (1983) applied 8 L of insecticide spray (insecticide + water) per tree, which is lower than reported elsewhere for ponderosa pine (DeGomez et al., 2006; Fettig et al., 2006b) and much

lower than our application rates. To that end, we applied approximately 3.5 times more volume per tree at twice the concentration. A study in the southeastern USA suggests differences in formulation within a.i. are likely to have little effect on drift resulting from single tree protection treatments (Berisford et al., 1991). In addition, Haverty et al. (1983) used spectrophotofluorometry for quantification of insecticide residues, which limits detection of finer particle sizes that are accounted for with HPLC (Pieper, 1979). In our study, detections were made up to 38.1 m from the tree bole with the use of HPLC (Table 3), whereas Haverty et al. (1983) reported that deposition was nearly undetectable at 12 m (i.e., the farthest sampling point from the tree bole in their study).

Table 4. Correlations between mean deposition and maximum deposition (mg carbaryl m^{-2}) at four distances from the tree bole and select stand and weather variables.

Distance	Dbh†	Basal area	Trees ha^{-1}	SDI	Cover	RH	Wind speed
m	cm	m^2 ha^{-1}			———%———		km h^{-1}
Mean deposition							
7.6	0.041	−0.139	−0.057	−0.131	0.042	−0.321*	0.528*
15.2	0.241	−0.233	−0.265*	−0.253*	−0.160	−0.509*	0.721*
22.9	−0.006	−0.153	−0.178	−0.167	0.005	−0.262*	0.275*
38.1	0.076	−0.187	−0.320*	−0.228	−0.172	−0.020	0.106
Maximum deposition							
7.6	0.057	−0.134	0.007	−0.085	0.013	−0.198	0.428*
15.2	0.186	−0.198	−0.137	−0.173	−0.131	−0.435*	0.655*
22.9	−0.012	−0.177	−0.039	−0.133	−0.017	−0.305*	0.352*
38.1	0.045	−0.134	−0.097	−0.082	−0.112	−0.026	0.056

* Significant at $P = 0.05$; data transformed before analyses.

† Values are Pearson's correlation coefficients (r), $n = 60$.

No significant correlations were found between mean or maximum ground deposition and tree diameter, basal area, or crown cover at any distance from the tree bole ($P > 0.05$, all cases; Table 4). We expected both basal area and crown cover to be correlated with deposition because both measures provide an indication of stand density, which is thought to influence drift. We observed a highly significant negative correlation between mean deposition and numbers of trees per ha at 15.2 and 38.1 m from the tree bole, but the relationship was not statistically significant at 7.6 m and 22.9 m or for maximum deposition values at any distance (Table 4). Similarly, stand density index (SDI) was negatively correlated with mean ground deposition at 15.2 m, but no other significant correlations were observed (Table 4). It is likely that higher levels of occupancy, as measured by numbers of trees and SDI, result in interception of drifting particles by tree boles and associated levels of foliage. However, this relationship was not well established in our study.

Relative humidity and wind speed were significantly correlated with mean deposition at 7.6, 15.2, and 22.9 m from the tree bole (Table 4). Both variables were significantly correlated with maximum deposition at 15.2 and 22.9 m and at 7.6, 15.2, and 22.9 m from the tree bole, respectively (Table 4). However, there was a highly significant negative correlation between relative humidity and wind speed ($r = -0.684$; $P < 0.001$). In the western USA, it is common for relative humidity to decline as temperature and wind speed increase throughout the morning. Wind speed is near constant during dark hours and follows a curvilinear pattern during daylight hours (Vining and Gregory, 1998). There was a strong linear relationship between wind speed and mean deposition, e.g.,

$$y = 0.207\ (\text{SEM} = 0.07) + [0.301\ (\text{SEM} = 0.03) \times \text{square root (km h}^{-1})],\ r^2 = 0.52;\ P < 0.001 \text{ at 15.2 m}$$

and wind speed and maximum deposition, e.g.,

$$y = 0.823\ (\text{SEM} = 0.14) + [0.487\ (\text{SEM} = 0.07) \times \text{square root (km h}^{-1})],$$
$$r^2 = 0.43;\ P < 0.001 \text{ at 15.2 m}$$

(Fig. 2A and 2B). Accordingly, wind speed was not only correlated with deposition but also seemed to influence the prevailing direction of drift (Fig. 3). As a result, we analyzed mean maximum deposition (i.e., maximum value collected on one filter per tree at each distance for each of 20 trees per orifice size) among treatments and found significantly greater levels for orifices #10 and #12 compared with #8 at 7.6 m ($F_{2,57} = 3.44$; $P = 0.04$) (Table 5). No other significant differences were observed ($P > 0.17$, all cases). Overall, distance from the tree bole significantly affected maximum deposition ($F_{3,236} = 187.1$; $P < 0.001$) (Fig. 4). Mean maximum deposition was greatest at 7.6 m (53.09 ± 5.68 mg carbaryl m^{-2}) and lowest at 38.1 m from the tree bole (0.28 ± 0.07 mg carbaryl m^{-2}) (Fig. 4).

Carbaryl is considered essentially nontoxic to birds; moderately toxic to mammals, fish, and amphibians; and highly toxic to honey bees (*Apis mellifera* L.) and several aquatic insects (Jones et al., 2003). Although single tree protection treatments are target-specific applications of limited extent (Hastings et al., 2001), drift may be deposited onto adjacent streams and lakes if appropriate no-spray buffers are not used. In the western USA, concerns generally involve effects on trout (Salmonidae) and aquatic invertebrates.

Rainbow trout (*Oncorhynchus mykiss* [Walbaum]) are native to and widely distributed throughout the western USA (Sigler and Sigler, 1996) and one of the most widely stocked and sought after game fishes in North America. Dwyer et al. (2005) conducted static acute-toxicity tests of five chemicals (carbaryl, copper, 4-nonylphenol, pentachlorophenol, and permethrin) on 18 freshwater fishes, including rainbow trout, and one amphibian. Generally, permethrin was the most toxic and carbaryl the least toxic to these species. The authors reported a 96-hr median lethal concentration that kills 50% of test organisms (LC_{50}) for rainbow trout of 1.88 mg carbaryl L^{-1}, which was one of the most sensitive species tested. A no or low-effect concentration of 0.94 mg carbaryl L^{-1} was also reported. This value is about 21.5 times greater than the highest concentration reported in Table 6. Other authors have used threshold values of 10% of the LC_{50} value on the basis that it poses no acute risk to aquatic organisms (USEPA, 1986; Bush et al., 1995). Using this criterion, we would also expect to see no observable effects on rainbow trout (Table 6). Little et al. (1990) observed no mortality of rainbow trout to 96-hr exposures of 0.01, 0.1, and 1.0 mg L^{-1} carbaryl. Swimming capacity (cm s^{-1}), swimming activity (s), and feeding were only affected at the highest concentration (1.0 mg carbaryl L^{-1}), which greatly exceeds our predicted values (Table 6). Peterson et al. (2001) reported carbaryl concentrations

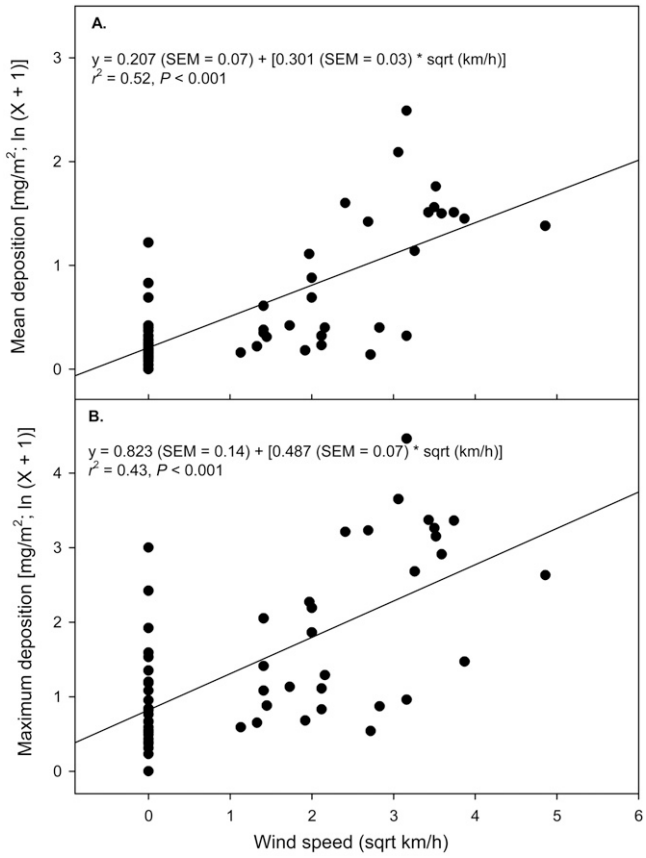

Fig. 2. Relationship between wind speed and (A) mean carbaryl deposition and (B) maximum carbaryl deposition (mg m^{-2}) at 15.2 m from the tree bole (*n* = 60), Wasatch-Cache National Forest, Utah, 2006.

of 0.0001 to 0.002 mg L^{-1} in Oregon streams and concentrations as high as 0.008 mg L^{-1} in brooks after aerial applications. Stanley and Trial (1980) reported peak concentrations of 0.0009 to 0.008 mg carbaryl L^{-1} in brooks and 0.0004 to 0.002 mg carbaryl L^{-1} in rivers shortly after spraying for spruce budworm (*Choristoneura fumiferana* [Clemens]) (Lepidoptera: Tortricidae) in Maine. Peak concentrations rapidly declined immediately after spraying and followed an exponential decay curve. The half-life of carbaryl was 25 h for all streams. Based on these reports, the amount of spray drift detected in our study poses little or no threat to rainbow trout in adjacent lotic or lentic systems.

Boone et al. (2004) examined the effects of 5.0 mg L^{-1} carbaryl in experimental ponds on larval Woodhouse's toad (*Bufo woodhousii* Girard) (Anura: Bufonidae) and southern leopard frog (*Rana sphenocephala* Cope) (Anura: Ranidae) and found that only toads were affected. Carbaryl exposure nearly doubled toad survival, which was attributed to an increase in algal food resources. Milam et al. (2005) provided no-observed effect concentrations of six chemicals to six freshwater mussel species and two standard (U.S. Environmental Protection Agency) test organisms (*Ceriodaphnia dubia* Richard and *Daphnia magna* Straus) (Diplostraca: Daphniidae). These mussel species do not occur in most of the western USA, but the study provides carbaryl toxicity data for freshwater bivalves, which are the largest group of invertebrates listed under the Endangered Species Act. No-observed effect concentrations ranged from 0.05 to 16.7 mg carbaryl L^{-1}, which exceed our predicted values (Table 6).

Relyea (2005) examined the effects of 0.51 mg carbaryl L^{-1}, among other pesticides, on several taxa in 1200-L polyethylene tanks. No significant effects ($P > 0.05$) were observed on the survival of insect predators examined, including *Anax junius* (Drury) (Odonata: Aeshnidae), *Tramea* sp. (Odonata: Lybellulidae), *Belostoma flumineum* Say (Hemiptera: Belostomatidae), *Lestes* sp. (Odonata: Lestidae), *Dytiscus* sp. (Hemiptera: Dytiscidae), and *Notonecta undulata* Say (Hemiptera: Notonectidae). Most of these species occur in lentic environments. Impacts to zooplankton were variable. No effects were observed for six species, significant increases in abundance were observed for two species, and a significant reduction was observed for one species (*Daphnia pulex* [Leydig]). The maximum single deposition value in our study (of 1920 individual filters analyzed) would result in a concentration of 0.54 mg carbaryl L^{-1} in 0.3048 m of water, suggesting drift resulting from single tree protection treatments also poses little or no threat to these organisms.

Carbaryl is highly toxic to stoneflies (Plecoptera) and mayflies (Ephemeroptera), which are widely distributed and important food sources for freshwater fishes. Acute toxicity studies of *Chloroperla grammatica* (Poda) (Plecoptera: Chloroperlidae) nymphs using a 96-h exposure period and a 1-h (pulse) exposure period resulted in LC_{50} values of 0.0051 and 0.0281 mg carbaryl L^{-1}, respectively (Jones et al., 2003). After the 1-h pulse exposure, treated nymphs were transferred to untreated water and monitored for 95 h. Although 50% of the nymphs were immobilized at 0.0281 mg carbaryl L^{-1} after the 1-h exposure, all nymphs recovered during the 95-h post-exposure period in untreated water (Jones et al., 2003). *Isogenus* sp. (Plecoptera: Perlodidae) and *Pteronarcella badia* (Hagen) (Plecoptera: Pteronarcyidae) are two of the most sensitive species for which carbaryl toxicity data are available. Mean 96-h LC_{50} values for *Isogenus* sp. and *P. badia* range from 0.0028 to 0.012 mg carbaryl L^{-1} and 0.0017 to 0.029 mg carbaryl L^{-1}, respectively (Mayer and Ellersieck, 1986; PAN Pesticide Database, 2007). Assuming a threshold value of 50% of LC_{50}, a 22.9-m no-spray buffer would offer sufficient protection for the most sensitive species (*P. badia*) reported above for orifice #8 but not orifices #10 or #12 (Table 6). The soil sorption coefficients (K_{oc} = 100–600) of carbaryl indicate the insecticide moderately binds to sediments. Thus, under natural exposure conditions, carbaryl may partition to sediments within the water column, which limits bioavailability and hence lowers toxicity (Jones et al., 2003). For example, Karinen et al. (1967) reported that 50% of carbaryl disappeared from estuarine water after 38 d in the absence of mud but that 90% disappeared after 10 d in the presence of mud. In 1991, carbaryl was aerially applied to 35,130 ha of rangeland at 560 g ha^{-1} (equal to 56 mg m^{-2}) and in 1993 at 448 g ha^{-1} (equal to 44.8 mg m^{-2}) to 23,504 ha (Beyers et al., 1995). A 152-m no-spray buffer was maintained around the Little Missouri River from which carbaryl levels and effects on aquatic invertebrates were measured. Carbaryl concentrations ranged from 0.0851 mg L^{-1} (1-h) to 0.0001 mg L^{-1} (96-h) after applications in 1991 and from 0.012 mg L^{-1} (1-hr) to 0.005 mg L^{-1} (96-h) in 1993. The 1-h value reported for 1991 is

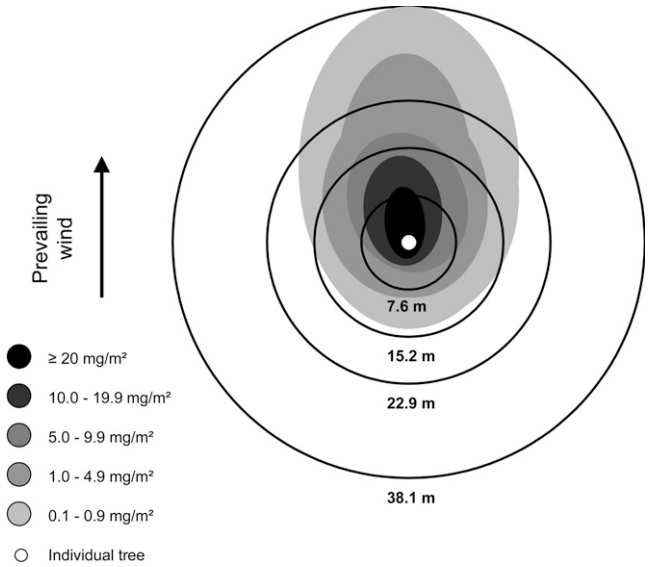

Fig. 3. Schematic depicting the distribution of average drift, Wasatch-Cache National Forest, Utah, 2006.

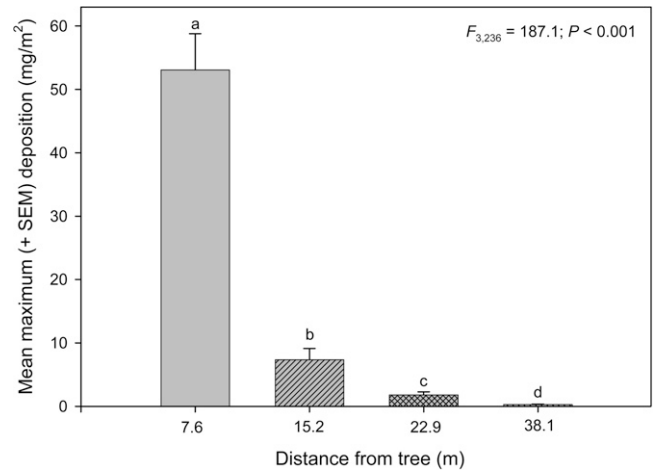

Fig. 4. Mean maximum deposition (+ SEM) of carbaryl (mg m^{-2}) at four distances from the tree bole after ground-based sprays to protect individual lodgepole pine and Engelmann spruce from bark beetle attack, Wasatch-Cache National Forest, Utah, 2006. Means followed by the same letter are not significantly different (Tukey's HSD; P > 0.05).

about twice as high as our largest predicted value (Table 6). Fish were unaffected, but an increase in the mortality of Ephemeroptera was observed immediately after the 1991 application, but not in 1993. No other aquatic invertebrates were affected. Subsequent collections showed differences were undetectable between affected and control areas. After rigorous analysis, the authors concluded that the ephemeropteran mortality probably represents a "worst case situation" because of low discharge in the Little Missouri River in 1991 (Beyers et al., 1995). Despite the high toxicity of carbaryl to Plecoptera and Ephemeroptera, few negative impacts are likely to occur from drift resulting from carbaryl treatments if reasonable buffers are used.

Conclusions

In this study, we documented carbaryl deposition resulting from single tree protection treatments. More than 80% of the insecticide applied stayed on trees. No significant differences were observed between tree species or among nozzle orifice sizes. However, at 7.6 m a strong trend was observed as lower levels of deposition occurred with smaller orifices (Table 3), and mean maximum deposition was significantly less for #8 than #10 or #12 orifices (Table 5). Orifice size had little effect on drift overall, but applicators concerned with short-range levels should choose a #8 orifice based on these data. Wind speed was correlated with drift up to 22.9 m from the tree bole (Table 4), and direction largely influenced the direction of prevailing drift (Fig. 3). Applicators should therefore be cognizant of wind direction and speed because in some cases they can limit ground deposition to sensitive attributes by accounting for these variables. Less drift is expected in dense stands (Table 4).

Based on the mean deposition values reported in our study, no-spray buffers of 7.6 m would be sufficient to protect freshwater fish, amphibians, crustaceans, freshwater bivalves, and most aquatic insects. Buffers ≥22.9 m would be sufficient for protection of the most sensitive aquatic insects (*Isogenus* sp. and *P. badia*). At the highest levels of carbaryl detected (of 480 filters analyzed at each distance), no-spray buffers of 7.6 m (maximum value calculated at 7.6 m = 0.54 mg L^{-1}) would be sufficient to protect most aquatic organisms. A buffer of >22.9 m (maximum value calculated at 22.9 m = 0.08 mg L^{-1}) but <38.1 m (maximum value calculated at 38.1 m = 0.01 mg L^{-1}) appear sufficient to protect plecopterans. Based on the evidence reported herein, we conclude that ground-based applications of carbaryl to protect individual lodgepole pine and Engelmann spruce pose little threat to adjacent lotic and lentic systems. No-spray buffers of 15.2 to 30.5 m, as typically specified in contracts or prescriptions for single tree protection treatments, seem appropriate.

Table 5. Mean maximum deposition (±SEM) at four distances from the bole of individual lodgepole pine and Engelmann spruce treated with 2.0% active ingredient carbaryl for protection against bark beetle attack, Wasatch-Cache National Forest, Utah, 2006.

Orifice size	*N*	7.6 m†	15.2 m†	22.9 m†	38.1 m†
8	20	38.19 ± 9.04 a	6.99 ± 2.44 a	0.99 ± 0.33 a	0.26 ± 0.13 a
10	20	53.69 ± 8.99 b	8.58 ± 4.38 a	2.29 ± 1.12 a	0.29 ± 0.07 a
12	20	67.40 ± 10.80 b	6.49 ± 1.79 a	2.09 ± 0.87 a	0.29 ± 0.16 a
		$F_{2,57}$ = 3.44; P = 0.04	$F_{2,57}$ = 0.54; P = 0.59	$F_{2,57}$ = 0.79; P = 0.46	$F_{2,57}$ = 1.82; P = 0.17

† Mean maximum ± SEM deposition (mg carbaryl m^{-2}) collected on one filter (9-cm diameter) per tree at each distance for each of 20 trees per treatment. Means followed by the same letter within column are not significantly different (P > 0.05; Tukey's HSD).

Table 6. Predicted concentration (mg carbaryl L^{-1}) in water at four distances from the bole of individual lodgepole pine and Engelmann spruce treated with 2.0% active ingredient carbaryl for protection against bark beetle attack, Wasatch-Cache National Forest, Utah, 2006.

Orifice size	*n*	7.6 m†	15.2 m†	22.9 m†	38.1 m†
8	20	0.0242	0.0038	0.0005	0.0001
10	20	0.0323	0.0047	0.0011	0.0001
12	20	0.0436	0.0035	0.0010	0.0001

† Mean concentration (mg carbaryl L^{-1}) based on assumption of mean deposition (mg carbaryl m^{-2}) into a static body of water 0.3048 m deep.

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