Journal of Economic Entomology Advance Access published August 11, 2016

Journal of Economic Entomology, 2016, 1–8
doi: 10.1093/jee/tow172
Research article

Forest Entomology

Lethal Trap Trees and Semiochemical Repellents as Area Host Protection Strategies for Spruce Beetle (Coleoptera: Curculionidae, Scolytinae) in Utah

E. Matthew Hansen,[1,2] A. Steven Munson,[3] Darren C. Blackford,[3] David Wakarchuk,[4] and L. Scott Baggett[5]

[1]US-Forest Service, Rocky Mountain Research Station, 860 North 1200 East, Logan, UT 84321 (matthansen@fs.fed.us), [2]Corresponding author, e-mail: matthansen@fs.fed.us, [3]US-Forest Service, Forest Health Protection, 4746 South 1900 East, Ogden, UT 84403 (smunson@fs.fed.us; dblackford@fs.fed.us), [4]Synergy Semiochemicals Corp, Box 50008 South Slope RPO, Burnaby, BC, V5J 5G3, Canada (david@semiochemical.com) and [5]US-Forest Service, Rocky Mountain Research Station, 240 West Prospect St, Fort Collins, CO 80526 (lsbaggett@fs.fed.us)

Received 5 May 2016; Accepted 5 July 2016

Abstract

We tested lethal trap trees and repellent semiochemicals as area treatments to protect host trees from spruce beetle (*Dendroctonus rufipennis* Kirby) attacks. Lethal trap tree treatments ("spray treatment") combined a spruce beetle bait with carbaryl treatment of the baited spruce. Repellent treatments ("spray-repellent") combined a baited lethal trap tree within a 16-m grid of MCH (3-methylcyclohex-2-en-1-one) and two novel spruce beetle repellents. After beetle flight, we surveyed all trees within 50 m of plot center, stratified by 10-m radius subplots, and compared attack rates to those from baited and unbaited control plots. Compared to the baited controls, spruce in the spray treatment had significantly reduced likelihood of a more severe attack classification (e.g., mass-attacked over strip-attacked or unsuccessful-attacked over unattacked). Because spruce in the spray treatment also had significantly heightened probability of more severe attack classification than those in the unbaited controls, however, we do not recommend lethal trap trees as a stand-alone beetle suppression strategy for epidemic beetle populations. Spruce in the spray-repellent treatment were slightly more likely to be classified as more severely attacked within 30 m of plot center compared to unbaited controls but, overall, had reduced probabilities of beetle attack over the entire 50-m radius plots. The semiochemical repellents deployed in this study were effective at reducing attacks on spruce within treated plots despite the presence of a centrally located spruce beetle bait. Further testing will be required to clarify operational protocols such as dose, elution rate, and release device spacing.

Key words: pheromone, bark beetle management, *Dendroctonus rufipennis*, carbaryl, MCH

The spruce beetle, *Dendroctonus rufipennis* Kirby (Coleoptera: Curculionidae, Scolytinae), is an eruptive forest insect and the major pest of North American spruce species, with ongoing outbreaks across many Rocky Mountain landscapes. To protect spruce trees from infestation, direct suppression strategies have been used to reduce or manipulate the local beetle population. Methods include preventative pesticide treatments, sanitation, trapping, and semiochemical strategies (Bentz and Munson 2000, Munson 2010). These methods vary in scale, efficacy, cost, and environmental impact. For example, preventative pesticide treatments using carbaryl are highly effective at preventing successful beetle attack (Fettig et al. 2006) but are used only for high-value individual trees, not stands, and pesticide applications are restricted to areas not affecting bee pollinator habitat and surface water, among others. Direct suppression methods for area protection to prevent spruce beetle infestation are not well-established and choices are currently limited to a few options with undetermined efficacy.

Trapping methods aim to suppress beetle populations, reducing the number of beetles which must mass-attack host trees to successfully overcome host defenses. Though there are examples of success (e.g., Schlyter et al. 2001), semiochemical-based mass trapping of bark beetles has a confounded history of protecting host trees (El-Sayed et al. 2006). While semiochemical spruce beetle attractants are well known, efficacy for host tree protection has never been demonstrated and spillover into live host trees is a common problem (Bentz and Munson 2000, Hansen et al. 2006a). Trap trees are a spruce beetle suppression strategy using felled, mature spruce to exploit spruce beetle's preference for downed spruce boles (Nagel et al. 1957). Dispersing adult beetles concentrate attacks on trap trees which can then be removed, burned, or debarked on site to kill all

Published by Oxford University Press on behalf of Entomological Society of America 2016.

life stages of the insect (Jenkins et al. 2014). This method is often deployed following logging operations (Hodgkinson 1985) and was used in conjunction with sanitation and semiochemical-based trapping to suppress a small, localized spruce beetle population in northern Utah (Bentz and Munson 2000). Nevertheless, trap tree efficacy has not been quantified for area protection of host trees.

A trap tree variation is to create a lethal trap tree by applying biocides to the tree which kills beetles upon arrival or soon thereafter. The lethal trap tree requires no further treatment and there is no risk of intensifying a local infestation in the event that the trap tree is not later treated to kill larvae and adult beetles. Early lethal trap trees used arsenical silvicides injected prior to felling to ensure the material was translocated throughout the bole (e.g., Lister et al. 1976), but these products are no longer registered for use in the United States. A modification is to apply insecticides directly to the bark of trap trees and early versions of this method (Hodgkinson 1985) also used insecticides no longer registered. A further modification is to apply semiochemical attractants to live, standing trees treated with insecticide, a practice that leaves the tree intact (Dyer et al. 1975). Fallen trap trees were observed to capture up to 10 times more spruce beetles than standing trees (Wygant 1960), but this advantage has been offset by advances in semiochemical attractants. For example, testing in Colorado, Wyoming, and Utah found that funnel traps baited with 1-methyl-2-cyclohexenol, frontalin, and a host terpene blend trapped as many beetles as fallen trap trees (Hansen et al. 2006a).

Currently, carbaryl is frequently prescribed by forest entomologists as a preventative treatment against western bark beetles (Fettig et al. 2006), maintains registration in the United States, and can be used for creation of lethal trap trees. Carbaryl is an acetylcholine-esterase inhibitor that prevents cholinesterase enzymes from breaking down acetylcholine, increasing both the level and duration of action of the neurotransmitter acetylcholine, which leads to rapid twitching, paralysis, and ultimately death (Hastings et al. 2001). Carbaryl is considered essentially nontoxic to birds, moderately toxic to mammals, fish and amphibians, and highly toxic to honey bees and several aquatic insects (Jones et al. 2003). If proven effective for area protection of host trees, standing lethal trap trees could be a suppression alternative when sanitation treatments are not an option. Regardless, the treatment efficacy of fallen or standing trap trees is not well documented in regard to protecting surrounding spruce (Hodgkinson 1985). Field research has documented the density and numbers of spruce beetles killed by trap trees (e.g., Lister et al. 1976) but, to our knowledge, none has quantified the degree of individual tree or area protection around trap trees. Additionally, Fettig et al. (2011) confirmed that bark beetles are killed by contact with carbaryl in laboratory assays, but field evidence of this effect has not been demonstrated and it is possible that carbaryl has some degree of repellency to bark beetles. Research is needed to quantify the efficacy of lethal trap trees for area protection of host trees and to determine whether carbaryl protects trees via lethal or repellent effects on bark beetles.

Semiochemical repellents can also be used to reduce or arrest bark beetle attraction to host trees, and MCH (3-methylcyclohex-2-en-1-one) is a well-known example for spruce beetle. Spruce beetle produces MCH (Rudinsky et al. 1974), which is an oxidation product of limonene or 3-carene (D.W., unpublished data), probably from microorganisms in the hindgut (Kinzer et al. 1971). In low doses, MCH acts synergistically with other semiochemicals to attract male and female Douglas-fir beetles (*D. pseudotsugae* Hopk.) but MCH becomes repellent in higher doses (Rudinsky 1973). Studies have shown that MCH reduced the number of spruce beetles attracted to logs infested with female spruce beetles (Kline et al. 1974, Furniss et al. 1976), traps baited with synthetic semiochemical lures (Furniss et al. 1976, Lindgren et al. 1989), or reduced colonization rates on stumps, windthrow, and felled boles (Rudinsky et al. 1974, Furniss et al. 1976, Dyer and Hall 1977, Lindgren et al. 1989). MCH has had mixed results, however, in protecting live, standing trees. Trials with passive release devices in Alaska and Utah were unsuccessful (Werner and Holsten 1995, Ross et al. 2004) whereas testing using microinfusion pumps as the release device found a 79-87% reduction in infestation rates compared to control plots (Holsten et al. 2003). Treatment success was attributed to consistent release rate with the microinfusion pump. These devices released 2.6–5.0 mg d^{-1} MCH regardless of temperature or time since deployment whereas previous passive releasers eluted 2–10 mg d^{-1} MCH at 22–25 °C but with variable rates depending on temperature and time since deployment (Holsten et al. 2003, Ross et al. 2004). A new high-dose, high-release passive device may overcome the limitations of earlier designs. Additionally, novel spruce beetle repellents have been identified using funnel trap bioassays conducted in northern Utah during 2013–2015 (D. W., E.M.H., and A.S.M., unpublished data) and these warrant further testing.

Our objective was to determine the efficacy of lethal trap trees, with and without deployment of repellents surrounding the trap tree, for protection of nearby untreated spruce. A secondary objective was to look for evidence that carbaryl-treated trees are killing, and not merely repelling, adult spruce beetles. Rather than attempt to quantify the numbers of spruce beetles killed by lethal trap trees, we surveyed posttreatment beetle attacks on spruce as a function of distance to the trap tree. This allowed quantification of protection, if any, to surrounding spruce as well as determination of the density of trap trees that might be required for operational use to suppress attacks. Testing was conducted at two areas, one with a building spruce beetle population and one with an epidemic beetle population. For repellents, we combined MCH in a high-dose, high-release bubble capsule with two repellent semiochemicals identified in recent testing. Combined with lethal trap trees, these repellents produce a "push–pull" effect that repels beetles from one group of trees and attracts them toward the lethal trap trees to suppress the local spruce beetle population (Progar et al. 2014).

Materials and Methods

Study sites were identified on the Duchesne Ranger District, Ashley National Forest ("Mill Park"), and Beaver Ranger District, Fishlake National Forest ("Big Flat"), Utah (Fig. 1). Our search criteria included sites with road access for ground application equipment, nearby active spruce beetle populations (assessed using aerial survey maps and confirmed with ground reconnaissance), and a majority of Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) component that included large diameter trees (≥40 cm diameter at breast height, dbh; Table 1). We considered the Mill Park area to have epidemic beetle population levels (two clumps of five or more infested trees every 2 ha; Bentz and Munson 2000) and the Big Flat area to have building population levels (>2 infested trees for every 2 ha). National Insect and Disease Detection Surveys (NIDDS) conducted during 2014 by the US Forest Service, Forest Health Protection staff indicated that there were 1,648 fading spruce (yellow-green needles) within 3 km of the center of the Mill Park area compared to 60 fading spruce within 3 km of the center of the Big Flat area (aerial detection surveys record spruce needle fade the year following infestation). Stands at Mill Park were partially cut about 40–50 yr

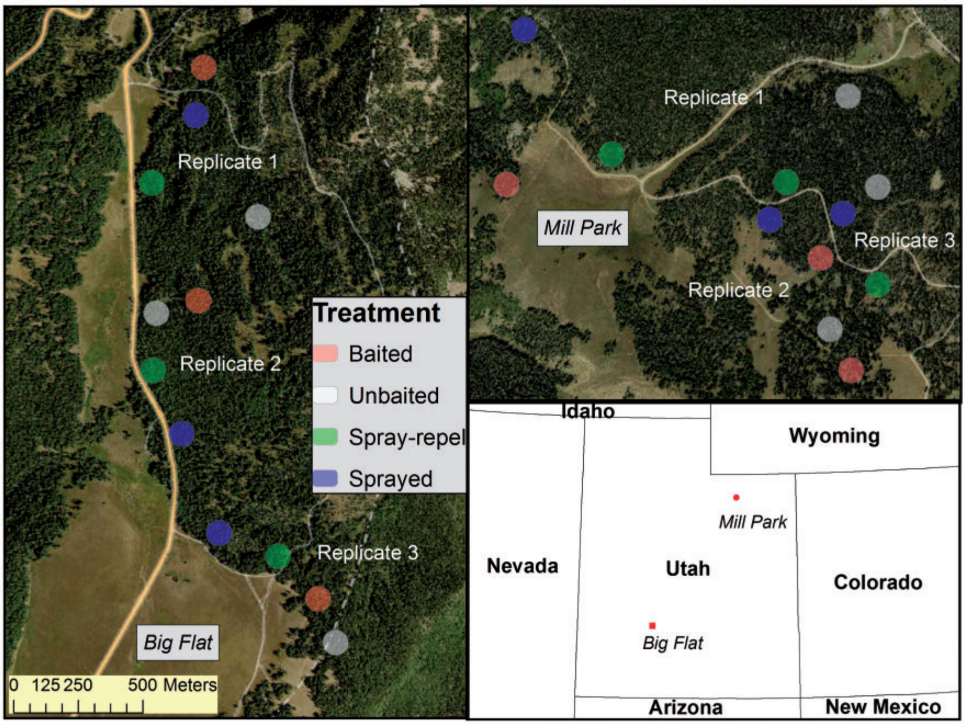

Fig. 1. Plot locations and treatments installed at "Big Flat" on the Beaver Ranger District, Fishlake National Forest, and "Mill Park" on the Duchesne Ranger District, Ashley National Forest, Utah. Total plot size was 50-m radius. Unbaited plots had no treatments applied. Baited plots had a three-component spruce beetle lure applied to an Engelmann spruce at plot center. Sprayed plots added carbaryl treatment to the baited spruce plus all spruce >20 cm dbh within 7.5 m. Spray-repellent plots added a 16-m grid of MCH and isophorone plus sulcatone throughout the plot (see Fig. 2).

Table 1. Pretreatment stand characteristics, by area, for each treatment for the entire 50-m radius plot (0.79 ha)

Treatment	Live BA (m^2, SD)[a]	ES BA (m^2, SD)[b]	ES dbh (cm, SD)[c]	Percent ES (%, SD)[d]	Recently infested BA (m^2, SD)[e]
Big Flat					
Unbaited control	42.6 (3.3)a	34.0 (6.2)a	43.2 (3.0)a	68.5 (9.1)a	0 (0)
Baited control	37.0 (5.0)a	32.5 (5.8)a	42.4 (2.5)a	70.4 (11.9)a	1.12 (1.25)a
Sprayed	38.4 (4.8)a	31.9 (8.8)a	43.7 (0.5)a	60.4 (16.2)a	1.56 (2.13)a
Spray-repellent	39.9 (3.3)a	34.1 (7.2)a	45.7 (2.5)a	64.8 (16.7)a	1.79 (1.55)a
Mill Park					
Unbaited control	20.4 (0.8)a	19.3 (0.4)a	35.1 (1.5)a	90.8 (10.4)a	0.42 (0.22)a
Baited control	25.7 (5.2)a	23.9 (5.8)a	34.8 (1.5)a	90.9 (4.8)a	0.50 (0.64)a
Sprayed	23.3 (4.1)a	20.3 (3.6)a	35.6 (2.5)a	84.1 (2.9)a	0.51 (0.38)a
Spray-repellent	20.5 (2.9)a	16.8 (3.6)a	34.0 (1.3)a	80.3 (9.6)a	0.17 (0.25)a

For each area, within the same column means followed by the same letter are not significantly different at $P > 0.05$ using tests of pairwise differences (Tukey–Kramer).

[a] Total live basal area (BA) for all species. Big Flat species were Engelmann spruce, subalpine fir, and quaking aspen. Mill Park species were Engelmann spruce, subalpine fir, and lodgepole pine. Spruce that were beetle infested during 2015 were recoded as live to estimate pretest conditions.

[b] Engelmann spruce BA.

[c] Average diameter at breast height of Engelmann spruce ≥ 25 cm.

[d] Percent of all live stems that were Engelmann spruce. Percent by BA can be derived by dividing ES BA by Live BA.

[e] Spruce BA infested during 2013 and 2014. Unbaited control plots at Big Flat did not have any recently infested spruce although two of three plots had spruce estimated to have been infested during 2012.

earlier, contributing to smaller average diameter trees and less basal area (BA) relative to plots at Big Flat (Table 1).

With the exception of unbaited controls, all treatments included a centrally located spruce baited with a commercial spruce beetle trap lure consisting of frontalin, 1-methyl-2-cyelohexen-l-ol, and a host terpene blend (Synergy Semiochemicals Corp., Burnaby, B.C., Canada). Treatments were: 1) unbaited control—plot without lures, insecticide, or repellents; 2) baited control—plot with a centrally located, baited spruce; 3) sprayed—plot with a centrally located, baited spruce treated with carbaryl (i.e., lethal trap tree); and 4) spray-repellent—plot with a centrally located baited spruce treated with carbaryl (i.e., lethal trap tree) and with repellent semiochemicals deployed in a grid pattern around the lethal trap tree. For lethal trap trees, we used a flowable 2.0% active ingredient carbaryl formulation (Sevin SL, Bayer CropScience, Research Triangle Park, NC) in water solution (pH = 6.5). Carbaryl was applied to the point of runoff at root collar using a #12 nozzle (0.475 mm orifice), reaching a height up to ∼15 m, on 8–9 June 2015 (Big Flat) and 16 June 2015 (Mill Park). We similarly treated all spruce >20 cm dbh within 7.5 m of each lethal trap tree. Repellents were MCH (1,000 mg bubble, eluting 12 mg d^{-1} at 25 °C), isophorone (1,800 mg bubble, eluting 6.5 mg d^{-1} at 25 °C), and sulcatone (1,700 mg bubble, eluting 35 mg d^{-1} at 25 °C). For spray-repellent plots, bubbles of all three repellents were stapled together on north bole aspects, ∼2 m above the ground, spaced on a 16-m grid surrounding the lethal trap tree (Fig. 2). Repellents were not applied to the lethal trap tree.

Three replicates of each treatment were installed at each of the two areas and each set of replicates (i.e., one each of all four treatments) was spatially grouped (Fig. 1). Plots were circular with a 50-m radius from the central spruce (0.79 ha). Adjacent plots were at least 60 m apart (i.e., minimum 160 m between plot centers). Because the sprayer hose had a maximum reach of 90 m and we were unable to find, at each site, 12 suitable plots with appropriate interplot spacing within 90 m of a road, treatments were assigned in a quasi-random manner. For example, we identified only nine plots with centers within 90 m of road access at Big Flat. Therefore, all six of the Big Flat sprayed and spray-repellent replicates were randomly assigned among those nine plot locations whereas the unbaited and baited controls were randomly assigned among remaining locations. Plots were installed before beetle flight, assessed by presence of brood adults under the bark of trees attacked during 2013 or 2014 and with no evidence of fresh attacks on live spruce. Big Flat plots were established 8–10 June 2015 and Mill Park plots were established 11–16 June 2015.

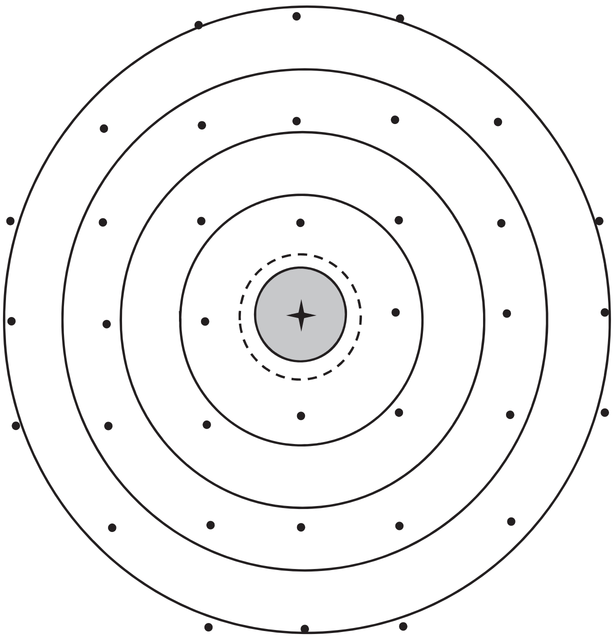

Fig. 2. Illustration of plot design. All treatments had a centrally located Engelmann spruce > 25 cm dbh (star). After new attacks on spruce were completed, we surveyed each plot by subplots every 10-m radius from plot center out to 50 m (black circles; data from 10-m radius and 10–20-m concentric ring subplots were combined for analyses; see Methods). Unbaited control plots had no treatments. Baited plots added a spruce beetle lure to the central spruce. Sprayed plots added carbaryl application to the baited tree (i.e., lethal trap tree) as well as to each live spruce >20 cm dbh within 7.5 m of plot center (shaded area). Spray-repellent plots added repellents MCH and isophorone plus sulcatone on a 16-m grid (dots) to the lethal trap and carbaryl-treated trees (shaded area).

After new attacks on host trees were completed, we conducted ground surveys of the plots to quantify posttreatment spruce beetle attacks. From plot center we delineated concentric rings every 10 m out to 50 m (Fig. 2). For each stratum we conducted a survey of all live trees >10 cm dbh and all spruce estimated to have been infested within the previous 10 yr (trees attacked before 2015 were a surrogate for local beetle population size). Data collected included species, dbh (measured with Biltmore sticks), status (live, spruce beetle mass-attacked, strip-attacked, unsuccessfully-attacked or "pitch-out," or other mortality), and year of attack. Year of attack was determined using characters described by Hansen et al. (2006b):

1. Current year attack—presence of boring dust and immature brood, occasionally pitch tubes, on an otherwise green-needled tree;
2. Previous year attack—symptoms range from fading needles to some or most needles fallen, live beetles may still be present, especially at the root collar;
3. Second year attack—fine twigs attached, most or all needles fallen, no live brood present; or
4. Older attack—no needles, some or many fine twigs missing.

Big Flat plots were surveyed on 21–22 September 2015 and Mill Park plots on 23–24 September 2015.

To determine whether carbaryl was killing arriving beetles rather than acting as a repellent, we installed collecting funnels at the bases of baited spruce at baited control and sprayed treatment plots at Mill Park. Single funnels (82 cm diameter) were deployed at ground level below the lures on north bole aspects to capture falling beetles. The funnels were installed on 24 June 2015 and collected three times through 10 July 2015.

Data analyses were complicated by the lack of currently attacked trees in the interior subplots (10-m radius) of any unbaited control replicates, a result that confounded error estimation. To address this problem, we collapsed data from the 10-m radius and 10–20 m concentric ring subplots into a single subplot whereas data from the other subplots were left as distinct.

The response variable "status" (2015 attacks only) describes attack severity and is ordinal, meaning that the categorical responses can be ranked but with unknown distances between classes (0 = unattacked; 1 = unsuccessful-attacked or "pitchout"; 2 = strip-attacked; 3 = mass-attacked). To address this response type, we analyzed the data with an ordinal logistic regression model (Hosmer et al. 2013). Each spruce tree is considered an experimental unit and the model results give the probability or likelihood of attack severity as a function of the treatment and the significant covariates. Because we included "replicate within area" as a random effect (i.e., we were not interested in quantifying the effect but needed to account for this source of variance), we used a generalized linear mixed model with a multinomial response distribution and the cumulative logit link function to accommodate this model structure (PROC GLIMMIX, SAS Institute, Inc., Cary, NC; Littell et al. 2006). Tested covariates included plot-level (i.e., entire 50-m radius plot) stem counts by infestation year for previously infested spruce, average dbh of spruce >25 cm (Schmid and Frye 1976), spruce BA, total BA, and the percent of spruce component. The dbh of each individual spruce was also tested as a covariate. To calculate stem counts of previously infested spruce, each mass-attacked tree (attacked during 2014 or 2013) was counted as 1.0 killed stem and each strip-attacked tree was counted as 0.5 killed stem. Pairwise comparisons were made using the Tukey adjustment for P-values and confidence limits (Kramer 1956).

We also used generalized linear mixed models (PROC GLIMMIX, SAS Institute, Inc.; Littell et al. 2006) to compare funnel captures at the bases of bait-only and sprayed/baited spruce to determine whether carbaryl was killing beetles. Replicate within collection date was included as a random effect. Denominator degrees of freedom were specified as Kenward–Roger type. Because captures were count data (i.e., counts of spruce beetles captured during each sampling interval), we specified a negative binomial response distribution.

Results

Spruce in baited control treatments were significantly more likely to be classified as more severely attacked (e.g., mass-attacked rather than strip-attacked, strip-attacked rather than unsuccessfully-attacked, or unsuccessfully-attacked rather than unattacked) than spruce in the other treatments for the 20-m radius, 20–30-m concentric ring, and 30–40-m concentric ring subplots (Table 2). For the 40–50-m concentric ring subplot, the baited control and sprayed treatments were not significantly different in likelihood of being classified with a higher severity beetle attack rating. Spruce in sprayed treatments were significantly more likely to be classified as more severely attacked than spruce in the spray-repellent or unbaited control treatments among all subplot sizes. Spruce in spray-repellent treatments were significantly more likely to be classified as more severely attacked than spruce in the unbaited control treatments for the 20-m and 20–30-m concentric ring subplots. These two treatments were not significantly different for the 30–40-m concentric ring subplot and the relationship was reversed for the 40–50-m concentric ring subplot as spruce in unbaited control treatments were significantly more likely to be classified as more severely attacked than spruce in the spray-repellent treatments. The largest differences in probability of more severe attack occurred between baited and unbaited control treatments as well as sprayed and unbaited control treatments for the 20-m and 20–30-m concentric ring subplot sizes (Table 2; Fig. 3).

Table 2. Odds ratios from an ordinal logistic regression model comparing the likelihood of a spruce stem being classified with a higher severity beetle attack rating (0 = unattacked; 1 = unsuccessful-attacked or "pitchout"; 2 = strip-attacked; 3 = mass-attacked) among treatment pairs

Plot-treatment pair	Odds ratio	Lower	Upper	Adj. *P*
20-m radius plot[a]				
Baited > Sprayed	1.7	1.4	2.2	<0.0001
Baited > Spray-repellent	13.6	8.8	21.0	<0.0001
Baited > Control	523.6	160.2	1711.0	<0.0001
Sprayed > Spray-repellent	7.9	5.0	12.3	<0.0001
Sprayed > Control	303.5	93.5	985.2	<0.0001
Spray-repellent > Control	36.1	11.2	132.8	<0.0001
Concentric ring 20–30 m from plot center				
Baited > Sprayed	1.6	1.2	2.0	0.0016
Baited > Spray-repellent	24.3	13.5	43.8	<0.0001
Baited > Control	373.8	115.1	1214.0	<0.0001
Sprayed > Spray-repellent	15.3	8.4	27.8	<0.0001
Sprayed > Control	236.1	73.4	759.3	<0.0001
Repellent > Control	15.4	4.3	55.3	0.0002
Concentric ring 30–40 m from plot center				
Baited > Sprayed	2.2	1.6	2.8	<0.0001
Baited > Spray-repellent	15.7	8.9	27.9	<0.0001
Baited > Control	21.1	13.5	33.2	<0.0001
Sprayed > Spray-repellent	7.3	4.1	13.1	<0.0001
Sprayed > Control	9.8	6.3	15.3	<0.0001
Spray-repellent > Control	1.3	0.7	2.6	0.8175
Concentric ring 40–50 m from plot center				
Sprayed > Baited	1.3	1.0	1.7	0.2582
Baited > Spray-repellent	17.7	8.6	36.7	<0.0001
Baited > Control	6.3	4.2	9.5	<0.0001
Sprayed > Spray-repellent	13.9	6.7	28.8	<0.0001
Sprayed > Control	4.9	3.3	7.4	<0.0001
Control > Spray-repellent	2.8	1.3	6.1	0.0434

The odds ratio is the probability that a spruce tree in the first treatment of the pair was classified as more severely beetle-attacked.

[a] Because the unbaited control treatment had only 0-severity classified stems (i.e., unattacked) in the 10-m radius subplots among all replicates, we combined data from the 10- and 20-m subplots to avoid problems with error estimation.

Generalized results can be obtained by evaluating the entire 50-m radius plots and data associated with only the mass-attacked classification (i.e., a summation of the subplot data displayed in the bottom panel of Fig. 3). The ordinal logistic regression model predicted mean mass-attacked status for 0.16% of spray-repellent spruce, 0.28% of unbaited control spruce, 2.51% of spruce in the sprayed treatment, and 4.70% of baited control spruce. Restated, mass-attacks were nearly twice as likely on spruce in baited controls compared to those in sprayed plots and >30 times more likely on spruce in baited control plots compared to those in spray-repellent plots. Also, mass-attacks on spruce in unbaited control plots were nearly twice as likely compared to mass-attacks on spruce in spray-repellent plots.

Recently infested spruce (combined 2013 and 2014 attacks) was a significant, positive covariate. Other significant, positive covariates were the percent of spruce in the canopy, average spruce dbh (stems ≥25 cm), and dbh of each spruce stem. Spruce BA was a significant covariate but had a negative relationship to the probability of a more severe spruce beetle attack.

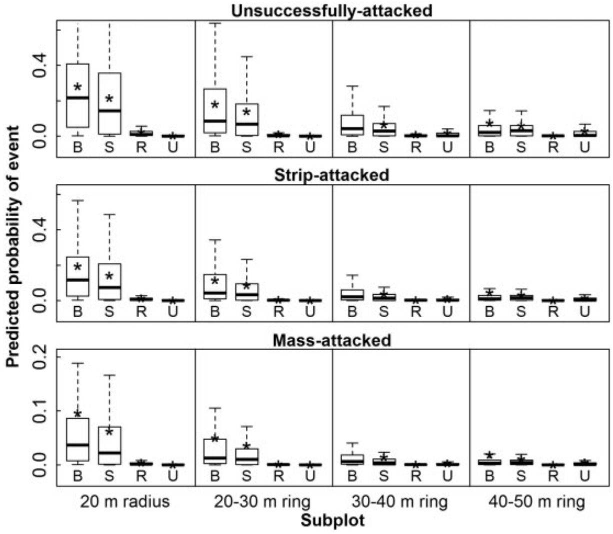

Fig. 3. Boxplots of predicted probabilities of spruce beetle attack by attack-type (rows), subplot (columns), and treatment (B = baited control; S = sprayed; R = spray-repellent; and U = unbaited control). Predictions are from an ordinal logistic regression model. The boxes show the 25th and 75th percentiles, the whiskers show 1.5 times the interquartile range from the box, the asterisks are the means, and the black bars are the medians (outliers not displayed for clarity). Note that the scale is different for the bottom panel (mass-attacked).

Fig. 4. Beetles collected in 82-cm-diameter funnels at the base of baited trees in bait-only and bait plus carbaryl-treated plots.

In the experiment testing for evidence that carbaryl-treated trees can kill beetles, funnels at the bases of carbaryl-sprayed trees had significantly more spruce beetles captured than those at bases of baited control trees ($F_{1,\ 14.19} = 24.35$, $p = 0.0002$; Fig. 4). Our samples suggest a possible temporally dependent relationship but we lack the data to investigate further.

Discussion

Spruce in the spray treatment had significantly lower probabilities of spruce beetle attack than those in the baited control treatment for each subplot size except the 40–50-m concentric ring (Table 2). Much of the difference for the 20-m plot appears to be related to trees protected by carbaryl. Out of 74 total carbaryl-treated trees, all of which were within 7.5 m of a three-component spruce beetle lure, only one exhibited signs of an unsuccessful attack while all others had no evidence of beetle entry. This confirms carbaryl efficacy as a preventative treatment against spruce beetle attack (Fettig et al. 2006). All successful new attacks within the 10-m radius subplots for the sprayed treatment occurred on unsprayed trees, spruce 7.5–10 m from plot center (data not shown). Additionally, we were able to confirm that carbaryl-treated trees were killing, not merely repelling spruce beetles (Fig. 4). Although our experiment does not exclude the possibility that carbaryl has some degree of repellency, our results are consistent with a hypothesis that beetles are attracted to the synthetic lure and are subsequently killed by carbaryl before a successful attack on a baited host tree.

Our objective was to determine if lethal trap trees could be a strategy to suppress local spruce beetle populations sufficiently to protect nearby untreated spruce. The significantly reduced probabilities of a more severe attack classification (i.e., unsuccessful-attacked over unattacked, strip-attacked over unsuccessful-attacked, or mass-attacked over strip-attacked) in the sprayed treatment compared to the baited control treatment suggests that this strategy was partially successful within a 40-m radius (Table 2). Nevertheless, spruce in sprayed plots (i.e., spruce outside of the 7.5 m Carbaryl treatment zone) were significantly more likely to be classified as more severely attacked than spruce in unbaited control plots. Therefore, we do not recommend the spray treatment as a stand-alone beetle suppression strategy although modification of our protocols could improve efficacy. Four of the six sprayed plots had successful attacks on untreated spruce within the 10-m radius subplot. This created natural sources of secondary attraction (Borden and Stokkink 1971), attracting more dispersing adult beetles into the plot and causing additional attacks on unsprayed trees.

Hypothetically, treating spruce further than 7.5 m from the lure could have mitigated the effect of secondary attraction. Comparing the baited and unbaited control treatments suggests that the effect of the lure is greatly reduced at each distal 10-m concentric ring. For example, spruce in the baited treatment were 374 times more likely to be classified with a higher severity beetle attack rating than those in the unbaited controls within the 20–30-m concentric ring whereas the likelihood dropped to 21 times more likely within the 30–40-m concentric ring. This suggests that creation of secondary attraction primarily occurred closest to the lure. It is possible that carbaryl treatment of all spruce within a larger radius from the lure (e.g., 20 m) would have prevented all lure-related attacks and, thus, averted creation of secondary attraction sources. Carbaryl treatment may be less practical and cost-effective, however, as the treated area increases although this will depend on the value of the site treated and existing population pressure. Alternatively, a less powerful lure at the center of our sprayed plots might have reduced or eliminated attacks on unsprayed trees, thus limiting the creation of secondary attraction. Regardless, lethal trap trees as a stand-alone suppression strategy using the protocols we employed would not be an effective strategy to suppress local populations of spruce beetle. Further research is required to determine if installing a less attractive lure and/or spraying a larger area with carbaryl might be effective in some situations. Isolated beetle populations infesting road accessible small landscapes of <100–200 ha near high value sites might be a candidate for this suppression strategy. Larger, inaccessible landscapes with epidemic populations are not a viable option for this treatment strategy.

In contrast, the spray-repellent treatment significantly suppressed spruce beetle attacks relative to the baited control treatment within each subplot size despite the presence of a centrally located spruce beetle lure (Table 2; Fig. 3). Even compared to the unbaited control treatment, spruce in the spray-repellent treatment had relatively little increased probability of beetle attack in the subplots near the lure and had reduced probability of attack in the outermost subplot. The probability of a mass-attack on spruce over the entire 0.79 ha of spray-repellent plots was about one-half of that for unbaited control plots (0.16% compared to 0.28%). These results suggest that the repellents, MCH and isophorone plus sulcatone, could be successfully deployed as an area treatment for high-value sites such as campgrounds.

Additional research is required to determine efficacy of each repellent as well as the optimal dose, elution rate, and spacing of passive release devices (*sensu* Ross and Wallin 2008, Ross et al. 2015). Our trapping bioassay data indicate that MCH is more active than isophorone plus sulcatone at repelling spruce beetles (D. W., E.M.H., and A.S.M., unpublished data). Additionally, spruce beetle population densities may affect efficacy and these repellents may be found to work optimally in combination with other treatments. For example, the mountain pine beetle repellent verbenone has been found to be effective in suppressing tree mortality but with reduced efficacy if deployed in areas with epidemic beetle populations (Progar 2005, Bentz et al. 2005). Spruce beetle repellents will require multiyear testing to confirm efficacy for a range of beetle population pressures and to account for possible changes in beetle behavior (*sensu* Progar et al. 2014). In the meantime, our results suggest that the high dose (1,000 mg), high elution rate (12 mg d^{-1} at 25 °C) MCH devices are able to provide area protection against spruce beetle attack. Our 16-m spacing resulted in about 39 g ha^{-1} MCH compared to 28–30 g ha^{-1} MCH recommended for use against Douglas-fir beetle (Ross et al. 2015).

In summary, we do not recommend lethal trap trees as a stand-alone suppression strategy for epidemic spruce beetle populations. They may be a viable treatment alternative for smaller but accessible landscapes and isolated, building populations of spruce beetles. Further refinement of this strategy could include increasing the number and area of carbaryl-treated trees and installing repellents in adjoining sites to push beetles toward the lethal trap trees as a push–pull suppression strategy. In the event of spillover into unsprayed trees, sanitation treatments will be necessary to prevent increasing the local beetle population and exacerbating host tree mortality. Suppressing building to epidemic beetle populations may require an integrated approach including some combination of lethal trap trees, fallen trap trees, baited funnel traps, repellents, and sanitation (Lindgren and Borden 1993, Bentz and Munson 2000, Borden et al. 2006, Gillette et al. 2012). Regardless, the demonstrated efficacy of semiochemical repellents (MCH and isophorone plus sulcatone) is the most promising technology revealed by our investigation. Additional research is required to refine deployment practices and confirm efficacy for a range of beetle populations. Based on our results, semiochemical repellents could be a viable treatment strategy for protecting individual trees and small areas (e.g., campgrounds) from spruce beetle attack, particularly if deployed as part of an integrated strategy that includes insecticide treatment and sanitation to protect high-value sites (Progar et al. 2014).

Acknowledgments

Technical help for plot installations and measurements was provided by Amanda Townsend, Jim Vandygriff, Valerie DeBlander, Andrew Giunta, Rob Cruz, and Jason Neumann. Danielle Malesky helped identify suitable study sites. Barbara Bentz and two anonymous reviewers provided helpful comments for previous versions of this manuscript. Thanks to Kathy Johnson and Andrew Orlemann (Fishlake National Forest) and Kristy Groves and Colette Webb (Ashley National Forest) for their cooperation. This study was funded by the Forest Service-Pesticide Impact Assessment Program. Semiochemicals were donated by Synergy Semiochemicals and carbaryl was donated by Chris Olsen, Bayer CropScience.

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