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Use of Semiochemicals for Southern Pine Beetle Infestation Management and Resource Protection

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Abstract

Since their discovery in the late 1960s, a number of semiochemicals have been identified and deployed for management of the southern pine beetle (SPB). Attractant semiochemicals are used routinely in the Southeast to survey and monitor SPB. Disruptant semiochemicals, primarily verbenone, have shown some promise for spot disruption, but they are not used operationally. Changes in releasers, uncertain demand, uncertain efficacy, and perhaps uncertainty about enantiochemistry have contributed to the current situation in which there is no semiochemical product with an adequate registration and demonstrated efficacy for SPB. Research interest remains, however, largely because there is a paucity of alternatives, semiochemicals offer great flexibility for treating forest resources at a range of spatial scales and resource values, they are generally less toxic than insecticides, and they are believed to be environmentally unobtrusive. Semiochemicals also offer easily observed and sometimes dramatic effects during initial testing. However, when applied for direct control or resource protection, disruptant and/or attractant semiochemicals have been plagued by inconsistent results. Difficulties associated with behavioral complexities, chemistry, performance of release devices, and a lack of knowledge about interactions with the environment have been identified as some of the factors responsible for poor performance. Improving on the research methods used to evaluate and predict semiochemical effects, along with determining the environmental factors that affect when and where semiochemicals can be efficiently and effectively deployed, are keys to their future utility as tools for bark beetle management.

26.1. INTRODUCTION

Direct control tactics against pine bark beetles are deployed when tree resources are imminently threatened. Semiochemicals have been used in this capacity for several decades, producing mixed results over many different types of applications. Some of the primary determinants in choosing a control tactic include the size, location (access), and value of the resource being targeted for protection. Suppression and protection efforts may target individual trees, a stand or smaller group of trees, or area-wide forests. Other considerations include host availability, time of year, costs, expected treatment efficacy, density of pest populations (observed as pest pressure), and the desired future forest condition. While tactics involving tree felling and insecticides traditionally have been employed to suppress southern pine beetle (*Dendroctonus frontalis* Zimmermann) (SPB) infestations, newer techniques utilizing semiochemical attractants and disruptants continue to be developed. In this chapter we discuss the current and potential use of semiochemicals for SPB suppression and resource protection across multiple scales of forest management.

The natural biological and ecological effects of semiochemicals are complex or unknown, making their successful application difficult. Compared to synthetic insecticides, semiochemicals are more flexible across a range of management unit sizes, but less so across bark beetle population densities (pressure levels). Semiochemical applications have been most effective when pest pressures were low or moderate (Bentz and others 2005, Borden 1996, Clarke and others 1999, Payne and others 1985, Progar 2005). Published results are skewed toward successful applications, and semiochemicals have frequently performed poorly when pest pressures or densities were high. In addition, real-world applications often produce results unlike those implied by trapping studies. In field tests, disruptant semiochemicals consistently have affected beetle behavior but have provided inconsistent protection of resources. A major challenge in improving their effective deployment for bark beetle management is the determination of conditions under which resources are sufficiently threatened to warrant semiochemical application but beetle pressures are not so severe that their use has a low probability of success.

Given the challenges and concerns associated with conventional methods of SPB control (e.g., synthetic insecticides and tree felling), the use of semiochemicals is likely to increase. In this chapter, we discuss why disruptant[1] semiochemicals have produced mixed, often unacceptable, results when deployed for managing bark beetles, even after more than 30 years of research and development. We detail the semiochemicals and elution devices used for SPB suppression and resource protection. We outline methods used to evaluate and develop semiochemical products and suggest why they may not accurately predict field efficacy or management utility. We also review the semiochemical tactics that have been developed for SPB and discuss advantages and concerns associated with their use. Finally, we discuss our vision of the future use of semiochemicals for protecting resources against losses to the southern pine beetle.

26.2. SEMIOCHEMICALS IN SPB MANAGEMENT

A number of semiochemicals have been identified that may have applicability in SPB management (Payne 1980, Vité 1970) (Table 26.1). In 1967, *trans*-verbenol and verbenone were identified from SPB (Renwick 1967), making them the first volatile chemicals identified from SPB that were believed important for influencing attack behavior. In the succeeding years, behavioral effects of these and other volatiles were reported for various *Dendroctonus* and *Ips* beetles (Pitman and others 1968, Renwick and Vité 1969). The identification of frontalin and its description as a primary cause of aggregation was reported (Kinzer and others 1969), and the activity of some major host volatiles was also described, including the primary role of α-pinene as a synergist to the attractant frontalin (Renwick and Vité 1969).

It has proven difficult to assign simple behavioral roles to other volatile compounds identified from SPB or its pine hosts. The behavioral effects of the semiochemicals listed in Table 26.1 represent our current understanding of their function. Response of SPB may also be influenced by dosage, purity,

[1] We use disruptant to indicate a semiochemical treatment that acts to disrupt the host selection process of beetles. We consider antiattractant, antiaggregant, inhibitor, interruptant, masking pheromone, and repellent as synonyms of disruptant. We hope this usage will promote consistency in terminology among stimuli that affect any of a range of behavioral modalities (e.g., vision) while causing similar measured effects; e.g., reduction in numbers caught.

Table 26.1—Semiochemicals that have been used in direct control efforts against the southern pine beetle

Chemical	Putative behavioral effect	Management application	Reference
α-pinene	Attraction synergist	Monitoring/ push-pull (when applied with frontalin)	Renwick and Vité 1969
Frontalin	Aggregation	Monitoring/ push-pull (when applied with host volatiles)	Kinzer and others 1969
Verbenone	Disruption	Resource protection	Renwick and Vité 1969
4-allylanisole	Disruption	Tree protection	Hayes and others 1994
(+)-*endo*-brevicomin	Attraction Synergist/ inhibition?	Uncertain	Sullivan and others 2007b
Trans-verbenol	Attraction synergist	Redundant with α-pinene; not used in direct control	Renwick and Vité 1969
Green leaf volatiles	Disruption	Resource protection	Dickens and others 1992

and stereochemistry, among other things. Verbenone is the most frequently applied disruptant semiochemical, but the behavioral effects of its enantiomers on the SPB have not been fully elucidated. Rudinsky (1973) suggested that high concentrations of racemic verbenone inhibited the response of SPB, while low concentrations synergized attraction. A similar pattern was indicated for myrtenol (Rudinsky and others 1974). The brevicomins, *endo*- and *exo*-, were first identified from *D. brevicomis* in 1968 (Silverstein and others 1968). It is still uncertain whether *exo*-brevicomin is a semiochemical for SPB (Payne and others 1978, Pureswaran and others 2008a); *endo*-brevicomin, however, has long been considered important in SPB communication (Payne and others 1978, Vité and Renwick 1971). *Endo*-brevicomin was first found in small quantities in SPB by Vité and Renwick (1971) and was regarded as a disruptant (Payne and others 1978, Vité and Renwick 1971). Its effects are proving complex, as it is now recognized as a potent aggregation pheromone when placed near, but not with, frontalin and host volatiles (Sullivan and others 2007b). This reversal illustrates how ideas for effective applications can change with increased knowledge. It is now apparent that the concentration and sequence of detection of semiochemicals encountered during host habitat-finding and host selection can affect beetle behavior. Beetle quality and time of year may also alter SPB response to semiochemicals (Berisford and others 1990, Salom and others 1995). These factors complicate the assignation of behavioral labels to semiochemicals. The inability to develop consistently effective semiochemical-based management tactics thus may be influenced by the inherently complex nature of bark beetle communication and behavior. Modalities in addition to olfaction are in play, and the semiochemical environment is a rich and dynamic bouquet of many chemicals and concentrations. These factors may weaken the ability of exogenous and predictable governance of beetle behavior by semiochemicals alone. In the past, the availability of any new semiochemical was often rapidly followed by quick and easy trapping studies and/or field applications. This semiochemical treadmill (testing one semiochemical after another *ad infinitum*) often resulted in conflicting or errant conclusions. Numerous chemicals satisfy the research desire for significant effects in trapping studies; precious few affect bark beetle dynamics in the field or impact forest management. A more careful and thorough approach with improved chemical detection technology and an increased understanding of the role of each semiochemical in host selection and colonization should result in more carefully designed field tests and potentially improved applications of semiochemicals.

26.3. SEMIOCHEMICAL DELIVERY SYSTEMS

Delivery systems are an integral component of semiochemical applications. Releaser designs for forest entomology have four primary goals: release a stable or at least predictable quantity of semiochemical over a useful duration; be inexpensive and rugged; protect the semiochemical from degradation; and provide for safe handling, storage, application and disposal (modified from Holsten and others 2003, Jutsum and Gordon 1989). It is also helpful if a design is appropriate for a variety of chemicals. Devices can be generally categorized using two schemes: the mechanism by which release is controlled (passive vs. active) and their deployment pattern in space (point-source vs. nonpoint-source).

Passive systems are by far the most commonly used for managing insects with semiochemicals. Passive devices are typically first-order emitters, providing a decreasing rate of release over time (Holsten and others 2003, Jutsum and Gordon 1989). They have no power source, and their release rates depend on a variety of extrinsic factors, including the vapor pressure and load of the semiochemical, climatic conditions, exposure, and construction materials. They are relatively inexpensive and qualitatively reliable, but may be prone to leaking and generally are not reusable. Passive devices can also cause storage difficulties (see below). Active devices contain a power source that helps control the release of the semiochemical. These devices often can be programmed to release controlled doses at specified intervals and may achieve zero-order emission; i.e., not dependent on diffusion (Holsten and others 2003). They can be expensive initially (although commercial costs for active semiochemical devices have not been determined), but may be refillable and reusable. Point-source systems are self-contained, discrete devices designed to be applied at specific spatial intervals; e.g., on a grid or on individual trees. Nonpoint-source semiochemical systems are designed to be sprayed or spread across a target area, including by air, for resource protection.

Figure 26.1—A frontalin pouch (left) and *endo*-brevicomin bubblecap. (right). Scale is inches. (photograph by Erich G. Vallery and S. Walters)

26.3.1. Passive Systems

Passive systems are the only device type offered commercially for use in forestry. For SPB, frontalin lures consist of two Eppendorf capsules containing frontalin, sealed in a brown polyethylene pouch (Figure 26.1). Currently, *endo*-brevicomin is released from bubblecaps (Figure 26.1).

In the past, host-based attraction synergists, such as turpentine or α-pinene, were usually released from glass bottles with cotton wicks. At present, these semiochemicals are emitted by diffusion from polyethylene pouches (Figure 26.2).

Commercially available verbenone release devices also consist of a pouch. A specified dose of verbenone is loaded onto a carrier material (e.g., sponge or cardboard tablet backing) and sealed within polyethylene sheeting to make a pouch (Figure 26.3).

26.3.2. Active Systems

The active systems that have been developed are all point-source systems. These devices have most frequently evolved from technologies developed for related purposes with larger markets (e.g., air fresheners). An exception is piezoelectric devices (El-Sayed and Byers 2000), which are specialty devices used primarily for research where quantitative control of release is paramount. They are the most precise and the most expensive (about $2,500). So-called "puffers" were initially designed for delivering air freshener in lavatories. They are not yet commercialized for use in forestry, and must be modified for use outdoors and

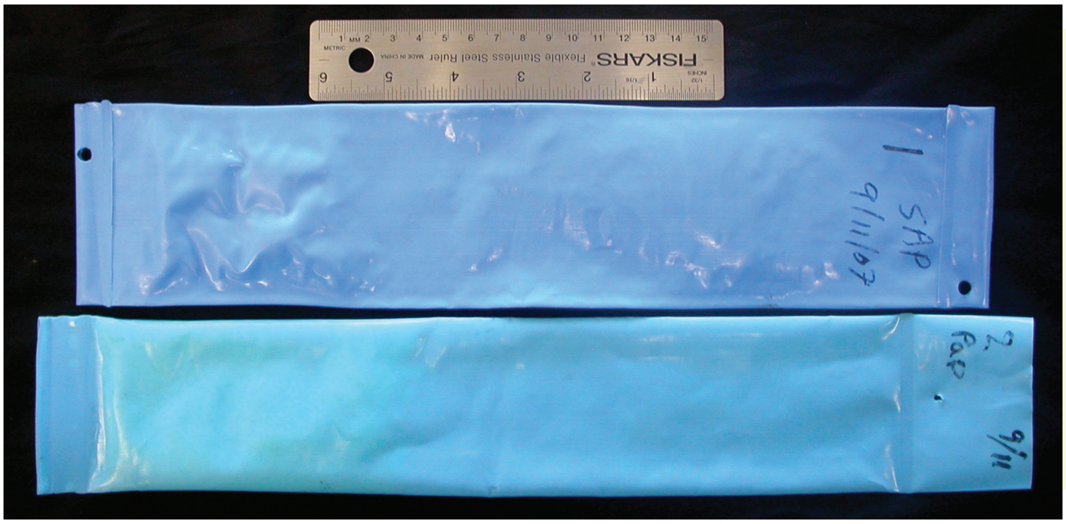

Figure 26.2— Commercially available polyethylene sleeves used to enclose host monoterpenes (e.g., α-pinene). Synergy Semiochemicals, Corp. (Burnaby, BC, Canada) ultra-high release a-pinene (upper); Contech/Phero Tech, Inc. (Victoria, BC, Canada) ultra-high release a-pinene (lower). Scale from 0 to 6 is inches. (photograph by B. Strom)

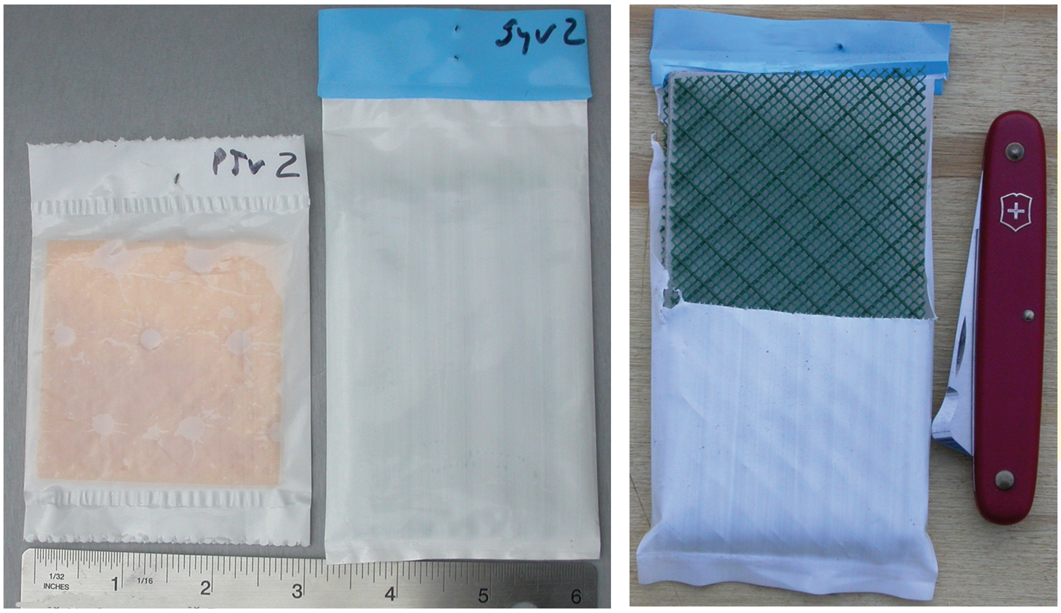

Figure 26.3— Commercially available verbenone devices for deployment against bark beetles. Contech/Phero Tech pouch (far left) and Synergy Semiochemicals pouch (BeetleBlock™ center and right). Scale is inches. (photograph by B. Strom)

with harsher chemicals (Figure 26.4). They hold promise for excellent controlled release at an intermediate cost (estimated at $30-$150 per device), but are unlikely to supplant passive devices in forestry applications unless the necessity for increased control of semiochemical release and semiochemical and device costs changes significantly.

The Med-e-Cell device (Med-e-Cell, Inc., San Diego, CA; Figure 26.5) is less expensive (estimated at <$10) and reportedly is close to being commercialized. It was designed as a general releaser for diverse products, including semiochemicals and air fresheners. Semiochemicals are moved from a reservoir by a controlled pumping process. Chemical release takes place from an emanation pad that is subject to environmental conditions, so properties of the pad (e.g., size and material) must be considered if effective semiochemical release patterns are to be achieved. Though the Med-e-Cell devices may offer improved control over semiochemical release, their performance in forest settings is uncertain as field tests are incomplete.

Active systems may also be programmable, offering the option of turning off the release of semiochemical when its effects are unnecessary (e.g., at night for daytime fliers). This feature can reduce semiochemical costs and waste. The future availability of active devices for use in bark beetle management depends on their

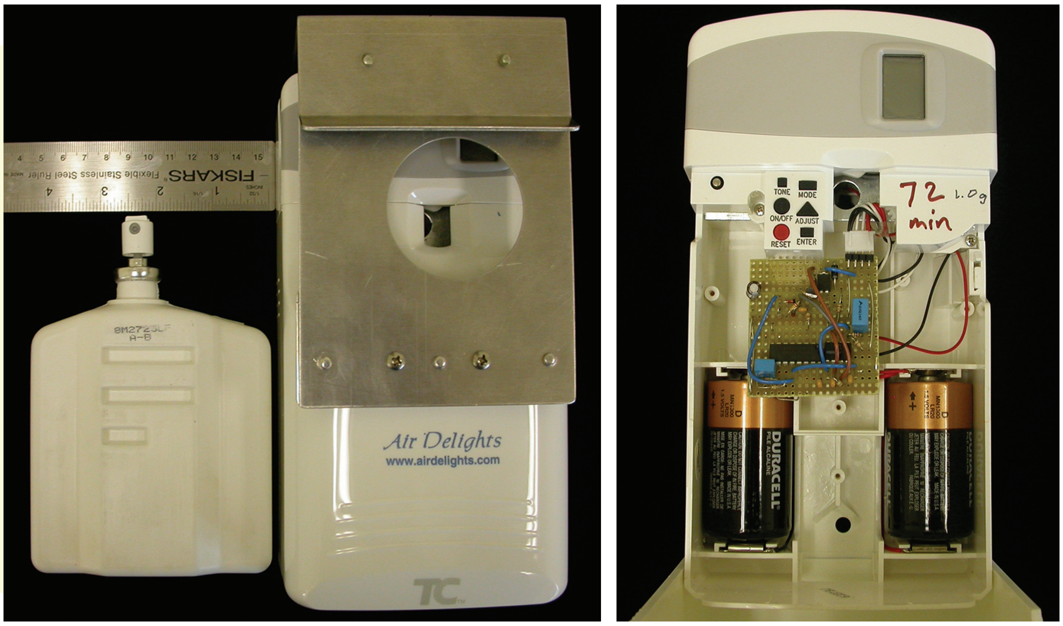

Figure 26.4—Puffer devices adapted for use with bark beetle semiochemicals from Air Delights (Air Delights, Inc., Beaverton, Oregon) lavatory air fresheners. Adaptations include a timer to vary the period between puffs, thereby determining the daily rate of semiochemical released from the reservoir. (Adaptations made by USDA Forest Service personnel at the Missoula Technology Development Center, Missoula, Montana). (photograph by B. Strom)

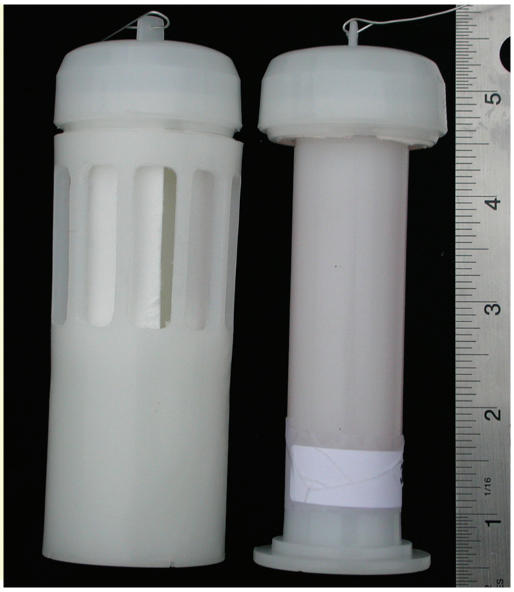

Figure 26.5—Prototype active, point-source releasers (pumps) developed by Med-e-Cell, Inc. (San Diego, California) to release bark beetle semiochemicals. Southern pine beetle verbenone releaser (left) was designed to release about 300 mg per day for 45 days. Western bark beetle version (right) was designed to release about 100 mg of verbenone per day for 3-4 months. Testing of performance in field applications has not been completed. (photograph by B. Strom)

ability to compete with simpler, potentially less expensive (but also less predictable) passive devices. Currently no active devices are registered for use in forest management.

26.3.3. Nonpoint-source Systems

Two types of nonpoint-source systems have been developed for bark beetles: those based on polymer microencapsulation (Payne and Billings 1989, Strom and others 2004) and those based on impregnated flakes or beads (Gillette and others 2009, Shea and others 1992). Registrations were granted in 2008 by the U.S. Environmental Protection Agency (EPA) for use of flakes (Hercon Environmental, Emigsville, PA) against bark beetles. Flake products are available for application against the Douglas-fir beetle, *D. pseudotsugae* (Disrupt Micro-Flake® MCH), and mountain pine beetle, *D. ponderosae* (Disrupt Micro-Flake® VBN), and can be applied by air or ground. The utility of verbenone-impregnated flakes for SPB management has not been evaluated, but they are currently not available with an enantiomeric blend that is suitable for SPB (see below). Their potential use will depend on efficacy, cost, convenience, and environmental effects relative to point-source devices.

26.3.4. Sharing Information on Releaser Performance

Many releaser designs have been developed by research and commercial entities with variable success. Improved dissemination and sharing of information on performance of elution devices (good or bad) is important for their efficient development and effective use. A Web page has been developed by the USDA Forest Service to promote exchange of this information (http://www.fs.fed.us/foresthealth/technology/elutionrate/).

26.4. ADVANTAGES OF SEMIOCHEMICALS FOR THE PROTECTION OF TREE RESOURCES

Semiochemicals are an attractive option for managing bark beetles, primarily due to their perceived lack of environmental intrusiveness, their flexibility, and their simplicity of application relative to other options. Standard practices for controlling SPB infestations are cut-and-remove and cut-and-leave. Pile-and-burn and cut-and-hand-spray with insecticides also have been utilized, but are labor-intensive and are used sparingly. Small infestations often are monitored until they become inactive or increase to a size requiring suppression. Insecticides were once commonly used in infestation suppression, but their use is currently limited to individual tree protection. Semiochemicals offer several advantages over these more traditional techniques.

26.4.1. Reduced Tree Felling

Current methods for infestation suppression all require tree felling. Tree felling is a particularly dangerous activity (USDL-OSHA), and is expensive if trees are not harvested. The development of new techniques incorporating semiochemicals could reduce the need for tree felling in response to bark beetle infestations or pressures, and if effective, would have broad management applicability, including use in special management areas where tree felling is prohibited or discouraged. Effective semiochemical treatments would also be beneficial during extended SPB outbreaks when sawyer availability becomes limited and/or when mills become saturated and low timber prices or lack of access preclude the utilization of cut-and-remove.

26.4.2. Host Specificity

Semiochemicals frequently are quite specific in their behavioral effects, reducing impacts on nontarget organisms as compared to synthetic insecticides or tree felling. Insecticides used against bark beetles are usually applied to the outer bole of either standing or felled trees, limiting nontarget effects in space when properly applied. However, insecticides affect a wide range of insects and may impact those that utilize the bole resource. Tree felling impacts not only SPB but all organisms that use standing trees for habitat and sustenance. Semiochemicals generally affect fewer nontarget species than insecticides, and even if behaviors of nontarget species are affected, individuals are not directly killed. Pheromones in particular tend to affect few species, usually the target insect along with co-occurring guild members and natural enemies. Competitors and natural enemies often use SPB pheromones as kairomones to find susceptible hosts or prey, so thoughtful positioning of SPB attractants can improve treatment efficacy. Salom and others (1995) report that verbenone treatments did not negatively affect SPB natural enemies. Host-based compounds tend to be less specific than pheromones, but are still much more specific than insecticides. Nontarget impacts of semiochemicals are more limited by species (to those that have altered behavior) but greater in space and perhaps time relative to insecticides.

26.4.3. Environmental and Human Safety

Human exposure to semiochemicals is generally low during applications for SPB management. Semiochemicals occur naturally, and related compounds are prevalent in forested environments, so neither the chemicals themselves nor their breakdown products are new to the ecosystems in which they are applied. Their targets are airborne, and significant quantities are not believed to lodge or persist in soil or water resources. The semiochemicals are enclosed within release devices, limiting the amount of human exposure. Proper handling and storage of the devices, plus care in their deployment, such as placing devices out of the reach of children, are essential for the safe application of semiochemicals. These practices are widely followed by forest health professionals.

Semiochemicals are believed to be less toxic to humans and other vertebrates than insecticides used for protective or remedial treatments of trees. For example, verbenone has been evaluated by Syracuse Environmental Research Associates, Inc. (2000). This report provides an oral LD_{50} in rats that ranges from 1 800 mg/kg (females) to 3 400 mg/kg (males). Dermal application of 2 000 mg/kg verbenone to rabbits did not result in any mortality. Synthetic insecticides with product labels for SPB include the active ingredients permethrin (Astro®, FMC, Corp.), with an oral LD_{50} of ~1 000 mg/kg (rat) and >2 000 mg/kg dermal (rabbit) and bifenthrin (Onyx®, FMC Corp.), which has an oral LD_{50} of ~150 mg/kg (rat) and >2 000 mg/kg dermal (rabbit).

Nontarget, nonacute impacts are difficult to evaluate and generally are considered less important than acute, more apparent effects such as toxicity. However, if semiochemical treatments shift from point-source release devices, which are usually removed following their use, to nonpoint-source broadcast applications of sprays, flakes, or beads, environmental impacts may require additional evaluation.

26.5. PROTECTION OF INDIVIDUAL TREES USING SEMIOCHEMICALS

Research into the use of disruptant semiochemicals for protecting individual trees from attack by aggressive *Dendroctonus* species has been ongoing since shortly after the discovery of scolytid disruptant pheromones in the late 1960s (Renwick 1967, Rudinsky 1968). It was quickly recognized that chemicals appearing late in the tree attack process may dissuade beetles from landing or constructing galleries, thereby providing the basis for a potentially useful management tool (Renwick and Vité 1970, Rudinsky 1969). In this realm, semiochemicals compete with insecticides, which can be effective but also expensive and environmentally intrusive. Evaluation of semiochemicals as tree protectants is usually limited to compounds with demonstrated disruptant activity in traps. Therefore, the question of primary interest with trees is not whether the treatment reduces attacks or even mortality; rather, it is whether or not effects are sufficiently large and consistent to prevent tree mortality at a useful level. Inherent in each evaluation are the environmental conditions of the study, especially the level of beetle pressure. To be most useful, studies must ascertain the conditions under which treatments succeed or fail. Semiochemicals have not fared well when two important efficacy criteria have been incorporated into their testing: evidence of demonstrated beetle pressure and a predetermined level of resource protection (efficacy) achieved (Shea and others 1984).

26.5.1. MCH

MCH (3-methylcyclohex-2-en-1-one) has been the most successful disruptant semiochemical used against bark beetles (Borden 1996, Ross and others 2002). It has been deployed primarily for the management of two species: the spruce beetle, *D. rufipennis*, and the Douglas fir beetle, *D. pseudotsugae*. It is well established that treatment of stands with MCH reduces the number of Douglas fir trees attacked by *D. pseudotsugae* (Ross and others 2002). The use of MCH to protect individual trees from *D. pseudotsugae* appears promising (Ross and Wallin 2008), but to date it has not been tested using standard protocols (Shea and others 1984). Applications of MCH for management of *D. rufipennis* are still only in the research and evaluation stage (Holsten and others 2003 and references therein), indicating that it is less effective in this system but its utility not yet elucidated.

26.5.2. Verbenone

Verbenone seems nearly ubiquitous among *Dendroctonus* and produces similar effects among other species when similar methods are used for evaluation. When deployed in traps in combination with attractants, verbenone typically reduces scolytid catch by 40-80 percent (see Borden 1996 for review). However, no published studies confirm the ability of verbenone to protect individual pines from SPB. Recent speculation that greater concentrations of R-(+)-verbenone provide greater disruptant activity than previously thought could renew interest in verbenone for this purpose, but the magnitude of its effects remain to be seen.

26.5.3. Nonpheromones

The most complete evaluation of a semiochemical tree protectant for SPB was done with the host-based disruptant 4-allylanisole (Strom and others 2004). This study evaluated efficacy under both major scenarios that cause tree susceptibility: proximity to attractants and compromised host resistance. 4-Allylanisole failed to provide efficacious protection of trees under either scenario. The inability of 4-allylanisole to deter all bark beetle species (e.g., *Ips*) may have contributed to treatment failure, particularly in trees with compromised resistance. To successfully protect these trees, a product must dissuade attack by numerous insect species, including those that may be more specialized for attacking decrepit trees. The disadvantages of semiochemical specificity are discussed below.

The recent commercialization of green leaf or nonhost volatile products may also affect semiochemical options for resource protection. However, extensive field testing has not yet been conducted, and there is no *a priori* reason to suspect these chemicals will improve upon the use of verbenone alone when deployed against SPB.

26.6. INFESTATION SUPPRESSION USING SEMIOCHEMICALS

The potential for using semiochemicals in suppressing bark beetle infestations has received considerable attention. In this application, managing the SPB is different than other

North American bark beetles because of SPB's affinity for spot formation. Spots provide a defined, biologically relevant unit to target for managing SPB and through which to evaluate success of applications. As discussed earlier, the predominant methods for suppressing infestations all include tree felling, so there is a need for identification and development of tactics that reduce or eliminate the need to fell trees. Even tactics that only slow resource losses until additional suppression activities can be applied may provide some benefit. New and evolving techniques using semiochemicals could fill these needs.

During outbreaks, SPB populations spend much of the year aggregated within expanding infestations. Therefore, semiochemical treatments can be targeted on known beetle locations and positioned according to semiochemical function and treatment objectives. Several tactics using semiochemicals have been tested or suggested for infestation suppression: trap and kill, spot disruption, and spot redirection.

26.6.1. Trap and Kill

Vité and Coster (1973) tested various trap designs for controlling SPB infestations. Traps were coated with sticky material and baited with frontalure, a 1:2 mixture of frontalin and α-pinene that was the standard attractant for SPB at the time. None of the tested designs attracted a sizable number of SPB, as beetles preferred to land on baited host and nonhost trees. The use of baited Lindgren multiple-funnel traps (Lindgren 1983), which provide an attractive vertical silhouette, has not been rigorously tested for infestation suppression. The consensus of SPB researchers and managers has been that baited traps cannot compete with the natural pheromone source surrounding trees under attack (although this is being revisited with the recent addition of *endo*-brevicomin to the attractant lure). Injections of trees with the herbicide cacodylic acid, or a combination of the fungicide metam-sodium and dimethyl sulfoxide (DMSO), have been proposed as techniques for suppressing spots (Roton 1987, Vité 1970). These injections render trees less suitable for brood development. Vité (1970) proposed a technique for utilizing cacodylic acid in spot suppression. Unattacked trees near the most recently attacked trees would be injected with cacodylic acid and baited with attractant to serve as trap trees, with the number of injected trees being approximately twice the number of currently infested trees. Copony and Morris (1972) tested this technique on 65 infestations. The closest unattacked pine to each currently infested tree was injected and baited with frontalure. In addition, every pine within 15 feet of a baited tree was injected. Additional treatments were only necessary on five infestations. Coulson and others (1973a) measured variables associated with the operational use of frontalure and cacodylic acid for SPB suppression in East Texas, and found that injected trees attacked by SPB still supported significant numbers of beetles (Coulson and others 1973b, 1975). As a result, this tactic has not been used operationally.

26.6.2. Spot Disruption

Halting the continued expansion of SPB infestations solely through the use of attractants has received little investigation. In one study, aerial applications of frontalure did not interrupt spot growth, and treatments appeared to increase beetle numbers on trees under attack (Vité and others 1976). Making applications from the ground, Richerson and others (1980) also tested frontalure treatments in active infestations. All trees with SPB larvae, pupae, or brood adults, as well as all nonhost trees within an infestation, were baited. Treatments successfully redistributed SPB within the infestation and prevented new trees from becoming attacked. Payne and others (1985) evaluated frontalure for spot disruption under intermediate and outbreak conditions; they concluded that the technique was more effective under intermediate conditions. This tactic has the potential to shift attacks to uninfested hosts near baited trees, and therefore may have more utility in spot redirection (described below).

Verbenone

Most SPB spot disruption tactics have focused on the use of the disruptant semiochemical verbenone. Early applications used a liquid polymer formulation (Payne and Billings 1989), but inconsistent release properties led to the use of a sponge or foam rubber pad sealed within a polyethylene pouch (Payne and others 1992, and similar to Figure 26.3).

In deploying verbenone against SPB, two tactics have been evaluated: verbenone-only and verbenone-plus-felling. In the former, all trees under attack plus a buffer of trees around the expanding edge of the infestation are treated with verbenone pouches. In the latter, all currently infested trees are felled and verbenone applied to a buffer around the infestation head. The size and shape of the buffers are similar to those applied in cut-and-leave treatments (Figure 26.6).

The elution device tested was a 4.5 x 7 cm cellulose sponge loaded with 5 ml of 34 percent R-(+): 66 percent S-(-) verbenone enclosed in a 6.5 x 10 cm pouch (1.5 mil thick white polyethylene; similar to the Contech/Phero Tech device shown in Figure 26.3). Pouches were tacked to trees at a height of 4 m using a Hundle hammer (Figure 26.7). Pouches were deployed so that they would be outside the reach of humans and approach the height of initial SPB attacks.

Field testing over several years supplied efficacy data from which treatment schedules were developed; Table 26.2 provides the number of devices required for efficacious treatment of infestations based upon these results.

The verbenone-only treatment was most effective on small to moderate-sized SPB infestations in pulpwood or plantations, while verbenone-plus-felling improved efficacy on larger infestations in sawtimber (Clarke and others 1999, Payne and others 1992). Large

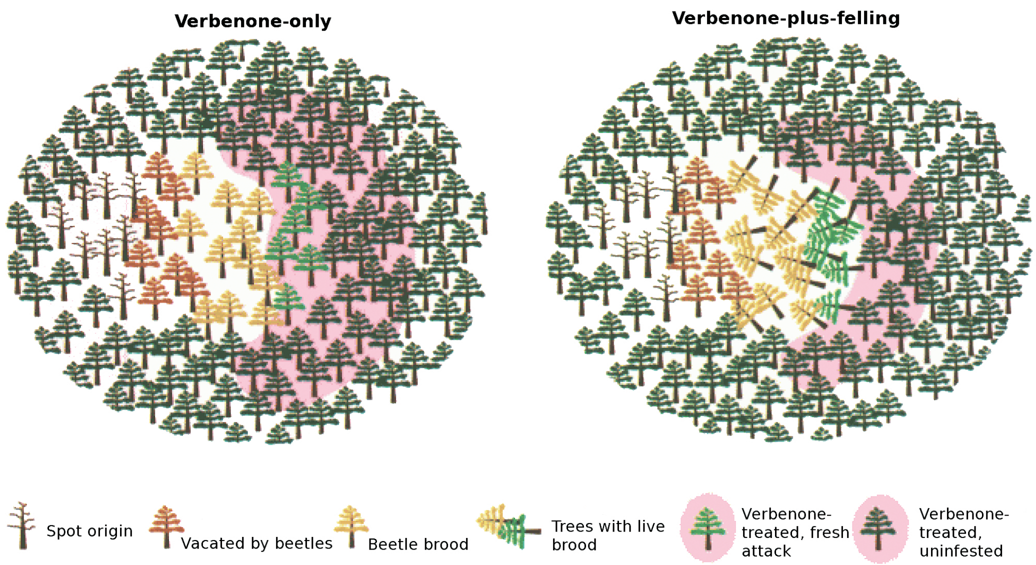

Figure 26.6—Diagrams depicting verbenone-only and verbenone-plus-felling treatments. (figure adapted from Clarke and others [1999])

Figure 26.7—The Hundle hammer (left), and pouch placement on treated trees (right). (photographs by S. Clarke)

infestations with large diameter trees are excluded from the table because the required number of pouches makes their treatment cost-prohibitive. These techniques have not been used operationally.

Hindrances to the operational use of verbenone

Operational use of verbenone with SPB has been hindered by a number of factors. Following the aforementioned efficacy trials, the sponge in the release device was replaced with a gel. The gel-based device was subsequently registered with the EPA by Phero Tech, Inc., and the application tables were no longer sufficient due to different release characteristics of the devices. This registration has subsequently lapsed, and the current Contech/Phero Tech verbenone pouches (Figure 26.3) have not been labeled for SPB. Synergy Semiochemicals Corp. has a verbenone device with a current EPA registration and a label for application against SPB (Figure 26.3). However, the label rates were determined for treating resources against mountain pine beetle, with an upper limit of 60 pouches per acre per year. This number is considered inadequate for most SPB applications (see Table 26.2). The enantiomeric ratio of verbenone that is necessary for effective deployment against the SPB has been researched (Salom and others 1995), and a 34 percent(+):66 percent(-) blend was used by Clarke and others (1999) to develop application schedules. There is recent concern that the most effective enantiomeric ratio of verbenone for SPB treatments may vary regionally or seasonally. It is hoped that an increased proportion of the R-(+)-enantiomer will reduce geographic sensitivity and required dosages, but this has not been tested, and the R-(+)-enantiomer is not as widely available as the S-(-)-enantiomer. Different formulations must be tested throughout the range of SPB to determine if significant increases in efficacy can be achieved through the use of regionally specific enantiomeric ratios. Treatment tables for SPB infestations will need to be developed for any registered verbenone products.

Table 26.2—Recommended number of pouches required to treat an SPB infestation, and their distribution by tree size. Large infestations with large diameter trees are outside of the range of the tables and are not recommended for treatment with verbenone. (Table adapted from Clarke and others (1999))

Verbenone-only

Average DBH (*in.*)	Number of Actively Infested Trees											
	10	20	30	40	50	60	70	80	90	100	110	120
6	50	50	50	63	79	95	110	126	142	157	173	189
8	50	56	84	112	140	168	196	224	252	280	308	335
10	50	88	131	175	218	262	306	349	393	437		
12	63	126	189	252	315	377	440	503				
14	86	171	257	342	428	513	599	684				

Verbenone-plus-felling

Average DBH (*in.*)	Number of Active Infested Trees											
	10	20	30	40	50	60	70	80	90	100	110	120
6	50	50	50	50	50	60	70	80	90	100	109	118
8	50	50	54	70	88	105	122	140	158	175	192	210
10	50	55	82	109	137	164	191	218	246	274	300	328
12	50	80	120	160	200	240	280	320	360	400	432	472
14	54	107	161	214	267	322	374	428	481	534	588	642
16	70	140	210	280	349	419	489	558	628	698	768	

Pouches per tree

DBH (*in*)	<4	8-May	14-Sep	15-17	18-19	>20
No. Pouches/tree	1	2	3	5	7	9

Semiochemical Combinations

Combinations of semiochemicals may improve the efficacy and/or reduce the cost of verbenone-based disruptant tactics while achieving the same or increased levels of effectiveness (Borden and others 2006). Combinations of verbenone and 4-allylanisole were tested on a small number of SPB infestations. The results were highly variable and the tactic was not pursued further (Clarke unpublished data). Green leaf volatiles can reduce SPB catch in attractant-baited traps (Dickens and others 1992), and nonhost chemical blends have been tested alone and in conjunction with verbenone against other bark beetle species (Huber and Borden 2001, Jakus and others 2003, Wilson and others 1996) with varying effects. Pheromones from competing species can disrupt the host selection process of more aggressive species. For example, (+)-ipsdienol serves as an attractant or disruptant for several species of *Ips* (Skillen and others 1997). *Dendroctonus brevicomis* males also produce (+)-ipsdienol, and *D. brevicomis* trap catch is significantly reduced when it is deployed in conjunction with verbenone (Bertram and Paine 1994, Byers 1982, Paine and Hanlon 1991, Strom and others 2001). The utility of nonhost volatiles or pheromones from other species for infestation suppression of SPB has not been tested.

26.6.3. Spot Redirection

Spot redirection seeks to shift the direction of spot expansion into areas that are more accessible for suppression or less suitable for continued spot growth. This tactic is equivalent to the push-pull management strategy used for many major insect pests (Cook and others 2007). In field trials, baiting uninfested trees with attractants in the direction of desired spot growth (pull), alone or in combination with a verbenone buffer around the previously expanding spot head (push), successfully redirected SPB infestation growth (Billings and others 1995). No operational use of this tactic has been reported. However, the increased attractiveness of SPB lures resulting from the addition of *endo*-brevicomin could rekindle interest in developing push-pull treatment methods for SPB, either for spot redirection or spot disruption.

26.7. AREA-WIDE SEMIOCHEMICAL TREATMENTS FOR POPULATION REDUCTION

Area-wide applications of SPB attractants or disruptants have been proposed as treatments for reducing the number and growth rate of infestations within a stand or forest. Gara and others (1965) suggest that field populations could be concentrated on trees or traps baited with attractants. Trees or traps could be arranged in groups or in grids, with trap trees being removed once they are colonized. Area-wide trapping or the timely removal of trap trees may also reduce numbers of natural enemies, so such treatments have been advocated for use during periods of low SPB population densities (Vité and Francke 1976), when impacts on the natural enemy community are presumed to be lower. Area-wide impacts of trap trees baited in the fall and spring during very low SPB population levels are under evaluation in East Texas. The proposed strategy is to concentrate populations of SPB on target trees during seasons when the developmental cycle of SPB is slowed by cool temperatures, thereby allowing more temporal flexibility for harvesting infested trees prior to brood emergence. Numbers of SPB in the western Gulf Coastal Plain have remained too low in recent years to adequately evaluate this strategy. Baiting trees following strip injection with cacodylic acid did not prevent the initiation of new infestations during outbreak conditions (Copony and Morris 1972). Vité (1970) proposed the baiting of trees scheduled for harvest to concentrate and then remove dispersing SPB; however, no tests of this tactic have been reported.

26.8. AREA-WIDE SEMIOCHEMICAL TREATMENTS FOR RESOURCE PROTECTION

Semiochemicals may be distributed throughout a stand or management area to reduce bark beetle attacks and tree mortality. For example, MCH has been applied in a grid pattern to prevent Douglas fir beetle infestations in susceptible stands (Ross and others 2002). Shea and others (1992) reduced mountain pine beetle attacks in lodgepole pine stands by using aerial applications of verbenone-impregnated beads. Borden and others (2003) suggest that a combination of verbenone and nonhost volatiles deployed at points throughout a lodgepole pine stand may provide short-term protection from mountain pine beetles. A push-pull strategy to protect high-value lodgepole pine stands from mountain pine beetles has also been tested (Lindgren and Borden 1993). The development of experimental and operational techniques utilizing semiochemicals for this purpose against SPB has not received much attention, primarily because SPB forms discrete infestations during much of the year rather than infesting scattered individual trees throughout a stand. Individual tree protection and infestation suppression using semiochemicals appear to have more practical value at this time.

26.9. CONCERNS WITH SEMIOCHEMICAL-BASED CONTROL TACTICS

The development and application of efficacious techniques for SPB management using semiochemicals comes with an assortment of challenges and concerns. Most important is their inconsistent efficacy. Why this continues to be the case is not certain, but improving our understanding of the semiochemicals, beetle behavior, and role of heterogeneous environments are thought to be keys to increasing the value of semiochemicals for forest management. Many of these problems can be addressed through research and treatment development prior to operational applications. However, it is possible that the complexities inherent with targeted manipulation of beetle communication are too great to allow for simple and robust forest management tools. Regardless of the reasons, there remains no semiochemical-based tactic that is being used operationally with SPB. We have identified some of the challenges associated with semiochemical-based SPB management strategies and divided them into three categories: 1. semiochemical identification and determination of behavioral effects, 2. semiochemical product development, handling and delivery, and 3. design and analysis of experiments.

26.9.1. Semiochemical Identification and Determination of Behavioral Effects

The activities of semiochemicals in an insect community are complex. Even though significant resources have been expended to increase our understanding, semiochemicals remain poorly understood. Pioneering work can sometimes be misleading. Misinterpretations or uncertainties of testing methods or bioassay results, incomplete understanding of the chemicals themselves, activity of mixtures, lack of understanding of insect behavior, and haste for a usable product. all complicate the interpretation of the role of semiochemicals in host selection and mating processes. While applications cannot wait for complete understanding (which likely will never be achieved), knowledge guides the thoughtful deployment of semiochemicals.

The research process for evaluating disruptant semiochemicals is multifaceted. Typically a potential semiochemical is discovered or identified by gas chromatography and mass spectrometry, having originated from the target or related insect, the host, a nonhost, or a combination. Serendipity and market factors also play a role in suggesting new compounds. Once a compound is identified and obtained, the behavioral effects that it causes can be determined. A first step in this process is to test whether the chemical elicits antennal activity in the target insect. This approach can evaluate complex plant tissues as well as individual compounds. Responses to different concentrations and enantiomeric ratios of the chemical often are evaluated. This is an effective method for determining a necessary step in organism response (i.e., the ability to detect the chemical); however, antennal activity does not indicate insect behavior relative to the chemical or necessarily provide a correlation with varying concentrations and behavioral effects in nature. Insects are faced with myriad chemicals during host and mate selection, so antennal response to an individual compound in the laboratory is hardly an indicator of its effects in the field. However, as a tool to filter complex mixtures for potential semiochemicals, antennal detection is unsurpassed.

Once a compound has been identified as a potential semiochemical, the behavioral effects must be determined. There is a paucity of effective whole-organism laboratory assays for bark beetles. The primary method has been a walking olfactometer and its variants (Berisford and others 1990, Hayes and others 1994, Payne and others 1976), but interpretation of results of these bioassays has been uncertain (relative to field results) and is considered as much an art as a quantifiable science. Wind tunnels have been used intermittently with bark beetles (Salom and

McLean 1991), but they have not consistently predicted field behavior and are not commonly used with these species. Because laboratory assays with bark beetles have not consistently produced repeatable or useful results, this step is often bypassed, and field trials are heavily relied upon to evaluate behavioral effects. Field trapping studies are the primary assay through which the nature and extent of semiochemical effects are evaluated; semiochemical utility is predicted from these results until efficacy evaluations can be achieved (see below).

26.9.2. Semiochemical Product Development, Handling and Delivery

Before field trials, and ultimately application tactics, can be realized, an elution method must be selected. The types of semiochemical delivery systems are described earlier in this chapter. Some of the factors influencing the selection of an appropriate elution method are trial or treatment objective, availability, desired concentration, environmental and forest conditions, and cost. Each semiochemical formulation and delivery system has its own set of benefits and concerns.

Consistency

To be successful, semiochemical treatments must be able to suppress infestations or protect trees throughout a wide range of forest and environmental conditions. Treatment results must be robust; i.e., effective and reproducible throughout the range of SPB. Some of the factors affecting consistency are:

Elution rate

Target elution rates are developed over time from observations and research and development; elution devices must be able to deliver chosen rates predictably. Release rates from passive devices, such as pouches, are affected by variables such as temperature, humidity, and sun exposure. Such devices must be designed to elute the semiochemicals at a specified minimum threshold level at the appropriate time of day. Active devices deliver a more certain quantity of the semiochemicals over specified time intervals. Though the release rates of active devices may not be as subject to variations in their environment, the diffusion of semiochemicals into the atmosphere after release is affected by weather conditions and climate. Selecting the appropriate number and placement of the elution devices can help ensure that the target elution rate is achieved.

Enantiomeric ratio

Many of the semiochemicals used in SPB management have enantiomers. Beetles may respond strongly to one enantiomer, while the other enantiomer may elicit no or even an opposite response. Elution devices must contain and release the target enantiomeric ratio and its rate to achieve the desired behavioral result.

Longevity

Devices must release their semiochemicals over a length of time sufficient to accomplish treatment objectives. As a rule of thumb, devices utilized in spot disruption should release the target elution rate for a time period equal to or longer than the length of an SPB generation at the time of application. Devices could be replaced or refilled as necessary.

Chemical degradation

Some semiochemicals can degrade into other compounds over time, affecting treatment efficacy. Temperature and sun exposure can affect the conversion rate. The addition of stabilizers, the proper placement of the devices, and device design, including the use of construction materials that screen out wavelengths that accelerate degradation, can help alleviate this problem.

Storage

Storage of elution devices can be problematic. Commercially available, passive devices are usually preloaded, so will elute semiochemicals at a temperature-dependent rate; they should be kept in cold storage to reduce losses and undesired exposure. The need to purchase, power, and maintain refrigerators or freezers dedicated to the storage of semiochemicals increases costs and can limit their use. Active devices normally contain semiochemicals sealed inside as free liquids, and consequently may require storage in outbuildings with regulated access, similar to insecticide storage.

Durability

In addition to delivering a desired rate of semiochemical over a specified time period, elution devices must be able to withstand a variety of conditions. Point-source devices must be positioned and secured so they cannot be dislodged by wind, animals, rain, or other factors. Nonpoint-source (sprayable) products must hold up under adverse weather and release for a period of time considered adequate for the application.

Retrieval

Reusable devices must be retrieved, and even disposable devices often are collected due to environmental or esthetic concerns. Applying the devices in a safe and secure manner increases the time and effort of retrieval. If retrieval is not planned, then treatments should incorporate biodegradable or environmentally safe materials. For example, aluminum nails can be used to attach pouches rather than steel nails that could damage equipment when trees are harvested and processed.

Cost

Semiochemicals often are expensive, and their application, especially in forested environments, can be time-consuming. Methods to contain costs include: 1. use of less expensive blends (impure chemistries and/or enantiomeric ratios) if efficacious; 2. development of reusable elution devices; and 3. applications during initial ground checks when infestations are smaller, also eliminating the need for a separate treatment visit. The drive to reduce costs also affects consistency. For example, the polyethylene tubing used in device (pouches or sleeves) construction also has other, larger markets that demand low cost over consistency. The resulting differences in allowable film densities may be great enough to affect elution rates from products constructed with these films.

Multiple Sources

The semiochemicals and materials used in device construction may come from multiple manufacturers. Any change in the materials can lead to a change in consistency, efficacy, and cost. Uncertainties about product consistency result in increased research, development, and purchasing costs.

Product Regulation and Environmental Protection Agency Registration

Semiochemical products are shipped throughout the world. The crossing of international boundaries causes cost increases and delays. In North America, semiochemicals and devices used for bark beetle management require EPA registration in the United States and its equivalent in Canada. Registration is a resource- and time-consuming process, and even maintaining registrations can be costly. Any changes in the semiochemicals or devices used can trigger the need for a new registration. Currently there are two semiochemicals with registered products for bark beetles: verbenone and MCH. Verbenone pouches are currently labeled to include treatment for SPB, but product revisions that occurred after extensive field testing and the pouch/acre limitations mostly preclude their use in applications against SPB. The registration of Hercon flakes with verbenone includes SPB, but the product is not offered with an enantiomeric blend that is suitable for application against SPB. There was a prior registration for 4-allylanisole, but it is no longer current.

26.9.3. Design and Analysis of Experiments

Testing and application of semiochemical-based tactics in the field have a unique set of challenges, many related to the concerns with elution devices detailed above. Semiochemicals have been available for evaluation for several decades, and experiences gained over this period suggest areas of particular importance for improving application methods for managing bark beetles. To date, methods have not been particularly reliable in their ability to accurately forecast the utility of semiochemicals for management of bark beetles.

Experiments to evaluate the effectiveness of semiochemicals can be challenging, and have not always used adequate methods. This is true both for trapping studies, which are simpler to design and evaluate, and as management-oriented applications (sometimes referred to as application experiments or administrative studies), which are frequently more challenging in these aspects.

Trapping Experiments

Initial field testing is typically done using funnel traps. Potential attractants are usually judged on their ability to attract higher numbers of beetles into a trap than the standard monitoring lure—in the case of SPB, a combination of frontalin and host volatiles. Disruptants are added to attractant-baited traps to gauge their ability to reduce attraction. Though the results of these trials may be encouraging, they may not be indicative of what occurs when semiochemicals are deployed for resource protection. Synthetic attractants are seldom competitive with natural attacks, causing disruptants to appear more (or perhaps less) effective than they are when deployed operationally.

Trap placement during field trials also can affect results. Historically, traps in SPB semiochemical field trials have been positioned near or within active infestations to ensure adequate numbers of beetles, and traps have been placed fairly close together (Hayes and others 1994). Studies by Turchin and Odendaal (1996) suggest that active radii of traps are fairly large (0.1 ha), and more recently, work by B. Sullivan (personal communication) suggests that measurable interactions may occur between semiochemicals on neighboring traps and from infestations. Traps assessing the behavioral effects of semiochemicals should be widely separated from other sources of attraction or inhibition to be considered independent replicates (Shea and others 1984). Also, we believe that traps should be located a minimum of 7 m, and probably further, from any uninfested host to prevent spillover attacks and the possibility of creating an additional source of attraction. Therefore trapping studies should be interpreted cautiously and, ideally, conducted in large areas with significant background populations of SPB, and with open areas or hardwood inclusions for trap placement.

Statistical analyses of trapping studies are frequently done using inadequate methods (Reeve and Strom 2004). Researchers analyzing trapping studies generally err on the side of methods being too liberally applied (Reeve and Strom 2004), suggesting that treatments appear better than their effects actually indicate.

Application Experiments

The designing of application experiments (i.e., those that test treatments in a management application or scenario) and testing of semiochemicals for infestation suppression can be problematic. Variability tends to be high, and accounting for the variability difficult. Large areas are frequently needed, and untreated infestations may be hard to come by in a randomly assigned structure. Each infestation is different, so variability is high and unexplained error can be large. Therefore, extensive testing is required to document treatment efficacy. Adequate replication is very important, but it is also time- and resource-consuming to achieve. Factors that affect the consistency of elution rates also affect treatment efficacy: time of year, precipitation, temperature, semiochemical formulation, and others. Infestation size and mean tree diameter also impact results (Table 26.2), as large infestations and/or large trees decrease the chance of successful SPB spot suppression. Multiple spot heads complicate treatment, and usually only one spot head can be successfully suppressed at a time.

Treatment Evaluations

Field trials of semiochemicals for infestation suppression must utilize active infestations and prevent further spot growth within set time limits and/or a designated treatment area. Payne and Billings (1989) and Clarke and others (1999) instituted a 1-2 week pretreatment monitoring period to ensure that only expanding SPB infestations were selected for treatment, and to provide a baseline for comparison with post-treatment growth rates. Though the pretreatment monitoring period provides multiple benefits, it also influences successful spot suppression as it may allow spot size to increase. Billings and Upton (1993) predicted tree losses in the absence of semiochemical treatment using the Arkansas spot growth model (Stephen and Lih 1985) to analyze treatment effects.

Clarke and others (1999) established three categories of efficacy:

1. Total suppression. Spot growth is stopped within 6 weeks and the treated buffer is not breached.
2. Partial suppression. Spot growth is reduced by at least 50 percent in 6 weeks, but trees outside the treated buffer are attacked.
3. Ineffective. Treatment failed to reduce spot growth by at least 50 percent within 6 weeks.

Similar infestation selection and treatment efficacy standards should be incorporated into future semiochemical field tests to avoid treating spots that will not grow regardless of treatment, or those that have low probabilities for successful suppression. Acceptable target efficacy rates that indicate a potentially operational suppression method have not yet been firmly established.

Individual Tree Protection

For individual tree protection, candidate semiochemicals that have exhibited promise in trapping studies are applied to pines, either at the head of an active infestation or that have been baited with standard SPB lures. Although somewhat different, both scenarios can provide a rigorous, demonstrable challenge to the disruptant, the former due to the magnitude of attractant in the vicinity, and the latter due to an extended period of attraction. Unlike insecticides, semiochemicals have rarely succeeded in protecting trees in these trials. The similarity of these tests to real-world applications is debatable and varies by environment. However, most management applications occur when a resource is imminently threatened, so tests should incorporate this notion in their design and ensure a rigorous challenge. It can be difficult and costly to achieve tests that demonstrate both sufficient beetle challenge and adequate (useful) tree protection. Long-term trials using at-risk or highly susceptible individual pines could be implemented, but achieving an acceptable mortality level of untreated trees could prove formidable.

Statistical methods for studies of semiochemical efficacy for protection of individual trees have been thoughtfully determined (Shea and others 1984) and applied by many researchers in the forest entomology community. These methods require that two criteria be met for a successfully completed experiment: demonstrated beetle pressure through attack of control trees and a demonstrated, predetermined level of tree survival in the population of treated trees. These procedures require a significant investment of resources and can easily result in insufficient beetle pressure because one has to predict whether beetle activity will be sufficient ahead of time. This is especially true for univoltine species. These methods are also more difficult to apply to species that form spots, such as the SPB, because infestations can start at experimental trees when attractants are used to challenge treatments. Methods that simply compare survival of trees in treated vs. control treatment populations are akin to trapping studies (i.e., they are primarily testing behavioral effects rather than efficacy) and in our view are much less useful.

26.10. FUTURE USE OF SEMIOCHEMICALS FOR DIRECT CONTROL OF SOUTHERN PINE BEETLE

We expect the use of semiochemicals for direct control of aggressive bark beetles, such as the SPB, to increase. This is especially true for disruptants, assuming their availability, and it is likely that their application will be at least somewhat independent of their demonstrated efficacy. There is a paucity of tools for managing SPB, and proven, effective tactics that include cutting trees are dwindling in their availability. Semiochemicals have an allure based upon the behavioral effects they cause; changes in numbers of beetles caught can be very impressive. Their deployment and comparison against a no-treatment option is often relatively uninformative, but continues to be used as a standard. This approach also promotes the semiochemical treadmill in which a variety of compounds, each having some level of demonstrated ability for reducing catch of bark beetles in traps, are deployed in a stream of tests without much regard for their utility in management. Semiochemicals also appeal to public land managers who wish to demonstrate that they have done something to suppress infestations or save resources, even if applications do not provide the desired result.

On the positive side, semiochemicals do produce behavioral effects in the target insect and offer hope in a package that is relatively unobtrusive toward the environment. As we learn more about their deployment, increase our chemical options, and improve release devices and tactics, we may determine combinations that are more efficacious. Most important, we may measure a sufficient number of environmental factors to provide more effective guidance on when and where semiochemicals can be efficiently and effectively applied to achieve an acceptable management result. This is the major challenge facing effective deployment of semiochemicals for direct control of bark beetles.