"Bark Beetles in a Pine Nutshell"
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This review of the literature and the recommendations that follow are intended to guide Los Alamos County residents in their response to issues brought on by the current bark beetle epidemic.

Introduction

Bark beetles comprise a group of beetles that look very similar in appearance but whose biology differs widely. There are some 6000 species of bark beetle worldwide with over 477 species in the United States. They more than likely originated in the Triassic period (200 million years ago) as evidenced through the dating of amber specimens containing trapped beetles which seem identical to some current day species (S.L. Wood 1982). According to the NMSU data base and Arthropod Collection, New Mexico is home to at least 15 genera of bark beetles and 37 species. Several of these are considered highly damaging to particular forest species. (*Dendroctonus* is generally ranked first, with *Ips* second, for destructiveness.)

Bark beetles in the temperate climates, including those here in Los Alamos County, are generally phloem feeders of conifers (phloeophagy). The phloem tissue of a tree is a thin layer rich in carbohydrates just underneath the outer bark. Ambrosia beetles, more common in the tropics, are Xylomycetophagous bark beetles. They will also feed on xylem tissue (wood) because they carry fungi that help to partially break this tissue down. Ambrosia beetles in general are not as host specific as their temperate siblings (S.L. Wood 1982).

All bark beetles have complete metamorphosis involving 4 life stages: the egg, C-shaped, legless larva and rice-grain-sized pupa can be found under the bark of their hosts. Adult beetles complete their development under host bark, chew their way to the surface and fly away to find a new potential host, mate and complete the life cycle.

These insects are considered secondary in an ecological sense, because generally they require a stressed or weakened host. Bark beetles play an important beneficial role in forest communities by breaking down dead and dying woody material, one of the initial steps in nutrient recycling. Their presence in standing trees signifies the occurrence of a stress or disturbance that predisposed the host to attack. More often than not, this predisposition can be associated with human activity. In natural forest systems, conifers can also be significantly stressed by mild winters, drought, wind, heat, wildfire and other abiotic and biotic factors, setting the stage for extraordinarily high bark beetle populations that become what we would call "outbreaks."

Selection and Colonization of the Host Tree

Bark beetles are among a small number of insect groups that bore into trees to lay eggs. In monogamous genera, including Dendroctonus (e.g., Western Pine Beetle, Red Turpentine Beetle, Mountain Pine Beetle), it is the female who selects the tree and mating location (nuptial chamber). The opposite is true for the polygamous genera of Ips, Pityogenes and Pityopthorus (e.g., Ips Beetle, Twig Beetle). With these genera, it is the male that begins the attack and eventually attracts several females. Upon selecting a tree for colonization, the attracting sex will release a special blend of chemicals called aggregation pheromones. However, in the monogamous Western Pine Beetle, both the female and her male partner will produce a unique blend of pheromone that when combined offers maximum attraction (Byers, 1983).

Bark Beetle Flights

Bark beetles generally disperse down wind due to wind drift, but in light winds the flight has been found to be nondirectional (Salom and McLean, 1989). On rotary flight mills, Ips were found to have the ability to fly on the average more than 24 miles without resting (Jactel and Gaillard, 1991). In another study, the longest continuous flight on a flight mill was 6 hours and 20 minutes. Two dimensional computer simulations show that bark beetles are capable of dispersing from a brood tree over wide areas while drifting with the wind. Ninety percent of the beetles become distributed over about a 20 square mile area within one hour of flight (Byers, 2000). Of course many individuals would be attracted to hosts or attacked trees much closer to their origin (Lindelow and Weslin, 1986). Some species may require a period of “flight exercise” before becoming responsive to semiochemicals (pheromones and host terpenes) while others are responsive immediately after flight begins.

Anecdotal evidence of long-range dispersal of bark beetles is inconclusive however in one study by Miller and Keen (1960) Western Pine Beetle infested islands of Ponderosa pine initially free of beetles that were separated from the main forest by large open sagebrush areas. They concluded that significant numbers of beetles must have flown as far as 20 km to reach the trees and kill them.

There are two theories on how bark beetles orient their flight in the search for suitable host material. The first is they orient over several meters to volatile chemicals released by stressed trees (called primary attraction). The second theory is that beetles fly about at random and land and test possible host material through short-range sight and tasting. The two theories are not mutually exclusive and either may operate as the primary mode in a given species. In addition to seeing and tasting possible host material, bark beetles also test possible host material for “resistance” (Berryman and Ashraf, 1970).

In addition to these two theories, bark beetles may find suitable host material by orienting to pheromones produced by competing species. For example, Western Pine Beetles respond to pheromones produced by Ips (Byers and Wood, 1981) and several species of Ips in the southeastern U.S. are cross-attracted to infested pine (Birch et al., 1980).

Acceptance of the Host Tree

Accepting a suitable host has been reviewed by Miller and Strickler (1984). They present a model where the decision of whether to accept or reject a given host plant is dependent on both external stimuli and internal inputs. As the bark beetle flies around searching for suitable host material they use up lipid reserves and become increasingly desperate to accept a host (internal input). The beetle will accept a host when the combination of host suitability and fatigue level are conducive. The suitability of the host is determined by the nutritional quality as well as existing beetle density (Byers, 2000).

Many species of bark beetle bore their holes in a uniform pattern suggesting that they are territorial in order to avoid competition (Byers, 1984). Some species, like the Five-spined Engraver, will bore through the outer bark of both host and non-host species before deciding on whether to accept. The amounts of glucose, fructose and sucrose occur in relatively the same amounts in most conifer species indicating some presence of feeding or reproductive stimulants (Byers and Wood, 1981). Few studies are available which indicate any isolation of these stimulants.

Resistance Mechanisms

The ability of a tree to resist colonization by bark beetles is a function of both tree vigor and the size of the beetle population. Resistance has long been attributed to the amount of resin exuded and the formation of pitch tubes (Webb, 1906). However, the establishment of bark beetles and the resulting damage has proven also to be dependant upon synthesis of toxic compounds called monoterpenes (e.g. oleresin). The process is highly energy consuming for the trees, so that bark beetles have developed a general strategy based on their weakening of the trees through mass attacks. Massive insect attacks comforted with inoculations of fungi carried by the beetles limit rapidly the resources of the trees. Every attack will then be successful and the trees will die.

The diversity in bark beetle biology with its resulting host tree specificity, has probably resulted from natural selection. It is also likely that each species of tree has coevolved various chemicals to defend itself. The disadvantage for the tree in this process is that the beetles may undergo hundreds of reproductive cycles compared to one generation of the tree. Although Gollob (1982) found higher content of the monoterpene myrcene in two apparently resistant pines that had survived an attack in an epidemic area, Raffa and Berryman (1982) found no relation between monoterpene composition and degree of resistance. Hodges (1979) also did not find a relationship.

The uppermost density of attacks that one tree can stand defines its resistance level. This level depends on the trees genetic background and overall health with a special emphasis on its hydric status (Raffa and Berryman, 1982). The variations in moisture levels and the resulting volume of resin flow is important in understanding the interactions of bark beetles and their hosts. Lorio (1986) has hypothesized that when there is adequate moisture the photosynthate (energy) is allocated primarily to shoot growth (cell division). Contrarily, when moisture levels are low photosynthate is allocated to cell differentiation, including the production of resin. This dimension seems to have an impact on the population dynamics of bark beetles. For example, periods of peak activity for D. frontalis (Southern Pine Beetle) coincide with periods of reduced moisture stress and reduced tree resistance (Lorio, 1986). Of course during times of severe drought there is little production of photosynthate for either shoot development or the synthesis of resin, which is why water becomes such an important part of the equation.

Fungal Associations

Associations of bark beetles with the fungi they carry can be complex. There are several general patterns. Associated fungi may be broadly divided among those species carried inside mycangia and those carried outside mycangia (Paine, Raffa, and Harrington, 1997). Mycangia are specialized structures on an insect designed to carry fungal spores and mycelia. Mycangia can be found on the thorax or in the maxillary and mandibular regions (mouthparts) of bark beetles. In some species, fungi are carried in open cuticular pits on the head, prosternum or elytra (wings). There are a number of fungal genera including both staining (e.g. Entomocorticium, Ophiostoma, Ceratocystis) and nonstaining genera (e.g. Ceratocystiopsis). Members of the genera Ceratocystis and the “blue stain” fungi (Ophiostoma minus) have not been isolated in the mycangia of bark beetles. This is important to understand as it appears that those fungal species transported on the external body surfaces of bark beetles (e.g. blue stain fungus) may help beetle colonization by reducing host resistance, while those fungi that are carried in the mycangia may also have a role in bark beetle nutrition (Paine, Raffa, and Harrington, 1997). In fact, although fungi carried on the external body surface play a role in the colonization of bark beetles through reducing tree resistance, they may actually be detrimental to bark beetle larvae, as evidenced by the avoidance of stained tissues by ovipositing bark beetle females (Franklin, 1970; Goldhammer, Stephen and Payne, 1989). In addition, it appears that less aggressive species of bark beetle may carry more strongly pathongenic species of fungi (Paine, Raffa, and Harrington, 1997).

One conclusion found in the literature on the relationship between blue staining fungi and tree mortality is that the fungus is required to cause death. However, other investigations suggest that tree mortality is the result of simultaneous rather than successive actions of the vector and pathogen (Berryman 1972).

Management Strategies

Mortality of high-value trees located in residential and developed recreational areas or administrative sites can occur as a result of stress associated with drought, overcrowding, injury due to construction, fire, soil compaction, vandalism and perhaps the initial stresses caused by forest thinning in the urban-wildland interface. Not all options in the following section are applicable to either the urban or the forest setting and are presented for discussion purposes.

Water

The importance of water in the production of photosynthate and the subsequent synthesis of resin has already been discussed (Lorio, 1988). During times of severe drought, high value trees should be given adequate water for these processes to take place.

Thinning

Bark beetles prefer moderate density stands because low density stands produce more vigorous (resistant) trees, low density stands have a less favorable microclimate and high density stands produce small trees with thin phloem and bark. They prefer older trees because older trees have less resistance to colonization. They are less able to produce a lot of resin, which is their main defense mechanism. Older trees also tend to be bigger and easier to find (Stand Susceptibility Index). Thinning practices should consider the population dynamics of bark beetles.

Reduction of Human Induced Stresses

The reduction of human caused stresses to trees can reduce the susceptibility of trees to colonization by bark beetles. This includes the reduction of root loss and damage, wounding of the trunks of trees, changes in soil type and depth, and increased exposure to wind and sun, and soil compaction. (Cain, Freeman and Rogers, 1996)

Removal of Brood Trees

The selection of suitable host material by bark beetles has already been discussed. Because beetles are attracted to hosts or attacked trees close to their origin (Lindelow and Weslin, 1986) it is widely suggested that when possible brood trees should be removed.

Semiochemical Disruption

The author is currently waiting for the latest (conference) proceedings of a recent conference on the practical uses of pheromones in controlling bark beetles from Barnes & Noble. However to date such strategies have only been successful prior to the outbreak of bark beetle epidemics. In these instances trap trees treated with pheromones have been used to concentrate beetles in a few selected trees which are then removed or destroyed. Many of these potential applications are still experimental.

Natural Predation

There is increasing evidence that natural enemies may be important in the population dynamics of some bark beetle species (Linit and Stephen, 1983; Miller, 1986; Weslin, 1992). Clerid beetles in particular are a major predator. There is evidence that Clerid beetle larvae can significantly impact the mortality of some species of Ips (Mills, 1985; Weslin, 1994). There is less evidence of the impact of adult Clerids feeding on adult bark beetles. Dodds, Graber and Stephen (2001) have also found some evidence of larval cannibalism of bark beetles by some wood boring herbivorous Cerambycids (e.g. Carolina Sawyer on Southern Pine Beetle).

Woodpeckers are also important predators of bark beetles. Not only does their feeding increase mortality, but also their scaling of the bark indirectly increases mortality. Woodpecker foraging favors predation by such insects as Clerid beetles and parasitic flies and wasps. As the birds strip more and more bark, surviving Clerid beetle larvae concentrate in the remaining bark, which increases the probability the remaining bark beetles will be consumed. In addition, bark thinning by woodpeckers makes bark beetle larvae more accessible to parasitic flies and wasps.

In outbreak situations, pest populations often increase in numbers far faster than their natural enemies; natural enemies "catch up" to their hosts when population growth slows to more normal rate. None of the natural enemies of bark beetles are available commercially to augment natural enemy populations or to do inundative releases.

Insecticides

Past attempts to suppress epidemics of pine bark beetle with chemical insecticides have been unsuccessful (Klein 1978). Recent research indicates that there are few options for direct interventions to manage pine bark beetle infestations on large or small tracts of land. Pine bark beetles can be prevented from successfully attacking individual trees by the application of chemical insecticides to the bole of the tree.

The federal government regulates pesticide use under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). FIFRA regulations require that all pesticide products be registered by the EPA prior to sale and/or use. Currently, several insecticides are labeled for "bark beetles" on "pine": carbaryl (Sevin), permethrin (Astro and "38" plus), some Metasystox (Metasystox-R) and azadiractin (Ornazin). Of these, carbaryl is probably least expensive and most available, with a long history of use in New Mexico for this and other pest problems. Four formulation of carbaryl carry current registration for bark beetles (Sevin XLR, Sevin SL, Sevin 4L and "7" by Monterey)

Several formulations of carbaryl have been evaluated and found effective for protection of individual trees from attack by bark beetles. The effectiveness and residual life of 1 percent and 2 percent suspensions of carbaryl (in the Sevimol1 formulation) for preventing successful attack of ponderosa pine by western pine beetle have been demonstrated (Hall and others 1982, Haverty et. al and others 1985). The effectiveness and residual life of a 2 percent suspension of the same formulation of carbaryl was confirmed for protecting lodgepole pine from attack by mountain pine beetle (Gibson and Bennet 1985). Evaluation of an additional formulation of carbaryl revealed that Sevin XLR provided excellent protection (90 percent survival) of lodgepole pine from mountain pine beetle for one season at 0.5 percent, one fourth the registered rate (Shea and McGregor 1987). Furthermore, a 1 percent suspension of either formulation provided very good protection (80 percent survival) for two seasons, while 2 percent provided excellent protection (90 percent survival) for two seasons.

In laboratory and cut-bolt bioassays, permethrin (Astro) also has been shown to be more toxic than lindane to the western pine beetle and the southern pine beetle (Hastings and Jones 1976, Hastings and others 1981, Smith 1982). Three rates of permethrin were evaluated for protection of ponderosa pine from western pine beetle; 0.2 percent and 0.4 percent provided excellent protection for at least one summer (about 4 months), but would not last through the second field season (about 15 months) (Shea et. al. and others 1984).

The effectiveness of registered application rates of the insecticide metasystox-R applied with Mauget tree injectors (INJECT-A-CIDE) was assessed in two strategies: (1) treatment of trees before western pine beetle attack (preventive treatment), and (2) treatment of trees after attack by western pine beetle (remedial treatment) for protection of individual, high-value ponderosa pine. This field test was conducted on the western slope of the Sierra Nevada on the Eldorado National Forest in central California. The registered use procedures for injections of metasystox-R were **not efficacious in controlling pine bark beetles**. (Haverty et. al. and others 1997).

The author has been unable to obtain efficacy trials for azadiractin (Ornazin EC). However in a personnel communication with Blair Helson, Research Scientist, CFS/GLFC/IPM Natural Resources Canada, who has worked extensively on the use of azadiractin for forest pest control, the author has been able to determine that there are **no field investigations which have looked at its use on bark beetles**.

There have also been efficacy studies on two other pyrethroids in addition to permethrin (esfenvalerate and cyfluthrin). These studies have indicated that these insecticides do provide protection against bark beetle (Haverty et. al. and others, 1998). To date the manufacturers have either not pursued or completed EPA registration for these insecticides.

Fungicides

The fungi associated with bark beetles are not affected by the application of insecticides and there are no fungicides registered for control of the fungi, especially after they are already growing inside the host tree.

Report Limitations

Since 1970 there have been over 4000 research papers on bark and ambrosia beetles (BIOSIS Previews Database, Philadelphia, PA.). Although the author has done a limited review of the literature in an effort to find answers to questions from clientele in Los Alamos County, it has by no means been exhaustive.

Secondly, the author has not had time to include evidence of the possible long-term ecological impacts that may result from the current epidemic. The author would suggest that council rely on Dr. Craig Allen, USGS and other ecologists for recommendations in this regard.

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