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CONTROL OF MOTH PESTS BY MATING DISRUPTION IN FORESTS OF THE WESTERN UNITED STATES

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INTRODUCTION

A specific objective of our project at the Pacific Northwest Forest and Range Experiment Station in Corvallis, OR is to determine whether mating disruption is a promising approach to control selected forest pests and to develop methods and materials for practical use. Disruption efforts have been directed mainly toward control of the Douglas-fir tussock moth, Orgyia pseudotsugata (McDunnough), the western pine shoot borer moth, Eucosma sonomana Kearfott, and the western spruce budworm, Choristoneura occidentalis Freeman. Preliminary work has also been done with the European pine shoot moth, Rhyacionia buoliana (Schiffermüller), (Daterman et al., 1975). Results with the spruce budworm are still tentative. Pheromone will substantially reduce reproduction by the Douglas-fir tussock moth and further tests are planned. Western pine shoot borer damage can be controlled with pheromone.

Constraints in Forestry

Insect control techniques for use in forestry have some constraints that are generally uncommon to agriculture. Locations may be remote and topography rough, and applications must usually be by aircraft. Treatment costs cannot be too high and frequent treatment is not usually acceptable. Treatment benefits are somewhat speculative because the economic impact attributable to a particular pest is often poorly understood. Exceptions would be situations where the death of an entire stand is threatened. Vertical spread of foliage in a forest is much greater than in a cotton field, and more material per hectare is required to get equivalent coverage.

Working Hypothesis

We adhere to several working hypotheses, or assumptions, when designing field tests. First, pheromone disruption success is inversely dependent on the insect's population density, other factors being equal. Tests with stored-product insects and observations in the field tend to support this (Sower and Whitmer, 1977; Vick et al., 1979; Sower et al., 1979a; Schwalbe et al., 1979). It is logical that an efficient distance communication is more important when insects are widely separated.

Response curves related to the dose of pheromone are believed to be rather flat (Figure 1) and significant increases in control appear to require at least 3-fold dosage increases. For dose/response data a wide range (100X or more) of dosages are tested. We think uniformity of coverage is much less critical than with contact insecticides.

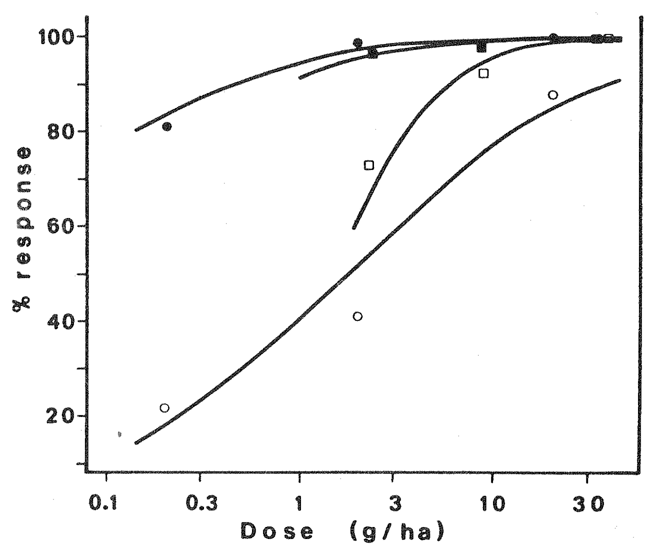

Fig. 1. Dose/response relationships. Criteria were captures of male western pine shoot borers in pheromone-baited traps (solid squares); captures of male Douglas-fir tussock moths in female-baited traps (solid circles); reduction of shoot borer damage (open squares); reduction of tussock moth reproduction (open circles). Curved lines are linear on a probability scale (not shown).

Large, isolated plots are preferred over small plots contiguous with adjacent forests because the impact of females which mate elsewhere and then fly into the treated plots is minimized. Our tests and perceived research needs, as outlined below, have been influenced by these assumptions.

Response Criteria

Criteria we have used to determine disruption effect, in order of importance, are damage reduction, mating reduction, and capture of males in female-baited or synthetic-pheromone-baited traps. Damage reduction, where it can be accurately assessed, is the definitive criterion for efficacy. Mating reduction indicates population control and suggests expected damage reduction. Measurement of mating reduction can be more precise where damage assessment is vague. Captures in female-baited traps indicate the efficiency of disruption of the pheromone communication; however, this does not necessarily indicate a corresponding control of populations or damage. Females often have the potential to attract 50 to 100 males in a lifetime, and mating is still most likely where this is reduced 95% to 2 to 5 males/female. Disruption of female-traps is a good criterion for preliminary tests. Likewise, disruption by synthetic baited traps is convenient for obtaining some kinds of information but should not be used to imply control of the insect.

WESTERN PINE SHOOT BORER

Eucosma sonomana (Kearfott) is a pest of ponderosa pine, *Pinus ponderosa* Lawson, and infests other pines in the Western United States (Stoszek, 1973; Stevens and Jennings, 1977). Larvae mine the pith of the terminal shoot of the tree causing an estimated 25% loss of height growth (Stoszek, 1973). Terminals are occasionally killed outright or break off at the exit hole, which promotes forking and economic degradation. Some lateral shoots, particularly in the first whorl below the terminal, are also mined, but this has little impact on the tree. Damage is most often noted in even-aged pine plantations, but pheromone-baited traps indicate the insect is also ubiquitous in naturally regenerating stands throughout the Western United States (Sartwell et al., 1980b). Trees in the 1.5- to 15-m height range appear most susceptible to damage.

Mating and oviposition occur early in the spring, often shortly after snow melts. Eggs are laid under scales on the pine shoot buds (Koerber, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA, unpublished). Hatching larvae burrow into the shoots and mine the pith. With occasional exception a single larva is present per shoot. Larval growth roughly parallels growth of the pine shoot. In midsummer, larvae bore an exit hole, fall to the ground, and pupate in the forest litter. Pupae have an obligatory diapause and will remain inactive until the following spring.

Population levels of *E. sonomana* are always low (a few hundred per hectare), perhaps because the numbers of preferred shoots in a pine stand are limited. Population levels are relatively stable from year to year. We have examined damage levels on a number of plots and have yet to find a natural population fluctuation >50% from one year to the next. The insect appears to be a classic "K" strategist (Southwood, 1977); that is, one with stable populations exhibiting arithmetic rather than logarithmic growth.

We were first approached by the Weyerhaeuser Company to consider developing pheromone disruption for control of *E. sonomana*. They considered the insect damaging to pine plantations, and no control methods existed. They had previously sponsored tests with conventional pesticides, including systemics, but these were found ineffectual, partly because the actively-feeding larval stage is protected by its location inside the shoot.

E. sonomana seemed an excellent target species for control by disruption of mating. It has a single generation each year with stable and predictable populations. Infestations and population levels can be quickly and accurately assessed. Further, its low population density suggested a particular vulnerability to control by disruption of the mating communication.

Pheromone Identification

Screening for potential attractants using field traps was considered a better approach to finding the sex pheromone than isolating and identifying compounds obtained from female extracts. Quantities of adult females are difficult to obtain because of their low field density, obligatory diapause, and related rearing problems. A number of compounds were tested on the basis of availability, known attractiveness to other Olethreutinae, or chemical similarity to such known attractants. Those few females that could be obtained were extracted and examined for the presence of compounds found active by the screening.

Males were strongly attracted to mixtures of (*Z*)-9- and (*E*)-9-dodecenyl acetates (Sower et al., 1979b). A ratio of 4:1 Z:E appeared to be present in gas chromatograms of female abdomen extract and approximated the optimum ratio for attraction of males. Minute nanogram quantities of this material formulated in PVC pellets (Daterman, 1974) will attract males about as well as live females. Given the low population densities of the insect, captures of 100 to 200 males/season per trap at 0.1 mg pheromone/trap bait indicate that the mixture is a very effective attractant. Accordingly, we consider a 4:1 mixture of the (*Z*:*E*)-9-dodecenyl acetate to be the sex pheromone of *E. sonomana*.

Disruption Tests

Application of pheromone in the field has repeatedly and consistently reduced the number of terminal shoots damaged (Table 1). Doses of 10 to 20 g of pheromone/ha applied using aircraft or 3.5 to 14 g/ha applied by hand were equally effective. Substantially lower dosages (0.2 to 2 g/ha by air) were not effective.

Table 1. Reduction in number of infested terminal shoots following pheromone disruption trials for western pine shoot borer.

Total area treated (ha)	Dose (g/ha)	Formulation	No. plots	Damage reduction (%)
8	3.5	PVC	3	83
4	14.0	PVC	3	84
20	15.0	Conrel®	3	67
100	20.0	Hercon®	3	88
600	10.0	Conrel	3	76

Controlled-release formulations using PVC (polyvinyl chloride) pellets applied manually and Conrel fibers and Hercon flakes applied from aircraft have been satisfactory for use with *Eucosma* (Overhulser et al., 1980; Sartwell et al., 1980a). All formulations still had 10 to 30% of their original pheromone content present by the end of the season. Treatment was in effect throughout the period during which moths were active (Figure 2). Plastic tarps located on the ground in clearings captured 54 to 63% of the respective intended dosages of Hercon and Conrel formulations, indicating satisfactory coverage of the plots. Stickers kept material in place adequately (Conrel) to totally (Hercon) over the season. Results with the Conrel formulation were consistent in both 1978 and 1979, the Hercon material was tested in 1979 only.

Pheromone release particles applied at various intervals, but which maintain similar total dosages, were about as effective. Only 100 to 400 PVC pellets were required/ha to get 3.5 to 14 g of pheromone/ha in contrast to 30,000 Conrel fibers/ha or 63,000 Hercon flakes/ha with respective pheromone doses of 10 and 20 g/ha. Consistent results (Table 1) with such diverse application patterns, but similar quantities of pheromone is remarkable. We plan further evaluation of effects of interval between evaporators as a variable separate from pheromone dosage *per se*.

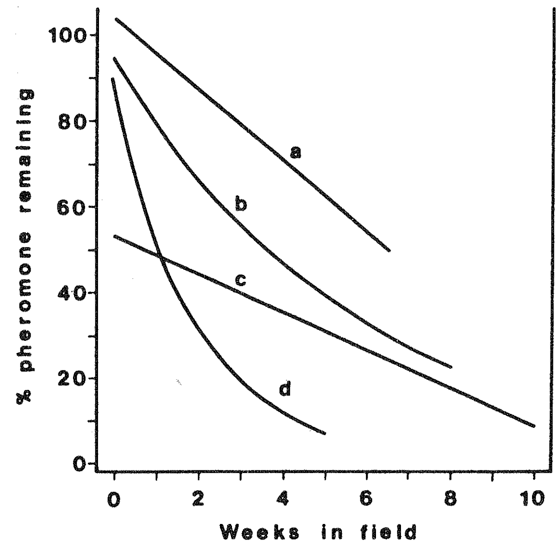

Fig. 2. Pheromone decline in controlled-release dispensers in the field. a) Z-6 Heneicosen-11-one for Douglas-fir tussock moth in Conrel fibers. b) 9-Dodecenyl acetates for western pine shoot borer in Hercon flakes. c) 9-Dodecenyl acetates for shoot borer in Conrel fibers. d) E-11 Tetradecenal for western spruce budworm in Hercon flakes. The end of each line approximates the end of the respective adult flight season which began during or after week 0. Weather was cool to cold for all data except (d) where temperatures were moderate.

Clearly, pheromone disruption can be used to reduce damage caused by E. sonomana. The pheromone appears to be registerable with the EPA in existing formulations. Toxicity of the pheromone appears very low based on various acute toxicity tests. Whether to use pheromone to control E. sonomana will now become an economic decision rather than a technical one. The specific question is: Will application on a given site cost less than predicted damage? This becomes an interesting point with E. sonomana since no previous control measures exist and, consequently, no previous guidelines exist on when to treat.

DOUGLAS-FIR TUSSOCK MOTH

Orgyia pseudotsugata is a serious defoliator of Douglas-fir, Pseudotsuga menziesii Franco, and true firs, Abies spp., in Western North America (Brookes et al., 1978). Small larvae prefer the more succulent new growth but late instar larvae will eat older needles. Tops of trees are usually consumed first, but in severe outbreaks complete defoliation of a stand can occur. Defoliation can result in top kill or death of the entire tree. Trees have to be almost totally defoliated before they are killed, and a stand may recover rapidly where defoliation is less severe (Wickman, 1979).

The Douglas-fir tussock moth is a sporadic pest. It is continually present throughout its range but normally at low to very low levels. Often the insect can only be detected by use of pheromone-baited traps. Sparse populations cause no damage; however, populations occasionally build rapidly to levels where damage occurs (Mason, 1979). Natural checks then catch up and the populations crash because of disease, parasitism, or starvation.

Tussock moth dispersal is passive -- the small larvae drift around on silk threads (Mitchell, 1979). Adult female tussock moths are wingless and mate and lay eggs on the cocoon from which they emerged. Adults emerge, mate, and lay eggs in the fall. The egg mass is the diapausing/overwintering stage. Hatch occurs in the spring about simultaneously with the growth of new foliage.

Development of pheromone disruption for control of the moth has been supported by the Douglas-fir Tussock Moth Research and Development Program. This program was formed in response to widespread outbreaks in Washington and Oregon in 1971 and 1972 which occurred coincidentally with the ban of DDT. The R&D Program supported development of a number of management methods including pheromone disruption. The final report of this program is a book which summarizes and updates available information about the Douglas-fir tussock moth (Brookes et al., 1978).

Pheromone Identification

The sex attractant pheromone of the Douglas-fir tussock moth was isolated and identified as (Z)-6-heneicosen-11-one (Smith et al., 1975). Daterman et al. (1976) suggested that additional unidentified co-attractants may also be released by the females, but none is nearly as effective as (Z)-6-heneicosen-11-one which is extremely attractive. Less than 0.5 μg of pheromone per 35 mg PVC formulated bait is sufficient for a survey trap and will last throughout the flight season with a maximum loss of only 10%. This kind of weak bait is used for insect survey traps where the survey objective is to capture numbers of males representative of the local population density. This survey system is now semi-operational, and is being deployed to provide early warning of sudden population increases concurrently with its final development (Daterman, 1978).

Disruption Tests

Pheromone application for mating disruption sharply reduces tussock moth reproduction. Pheromone applied at 9 to 36 g/ha in

110 to 450 g of Conrel fibers/ha reduced tussock moth reproduction by nearly 100% in a low density population in southern Oregon (Table 2). Dosages of 36 g/ha in Conrel fibers decreased reproduction by almost 80% in an outbreak population in New Mexico (Table 2). Formulations suitable for hand application, developed by Bend Research, Inc. (Sower and Daterman, 1977), had previously yielded similar results (Table 2). Dosages are not directly comparable because the manual application was confined to a single level 1.5 m above ground whereas trees, and presumably the aerially applied fibers, were up to 30 m. Pheromone applied at 1.5 m has little effect at 20 m (Sower and Daterman, 1977).

Table 2. Mating reduction following pheromone disruption of Douglas-fir tussock moth.

Treated area (ha)	Dose (g/ha)	Number plots	Population density	Mating reduction (%)
		Bend Research Formulations		
3.0	<1.0	3	low[1]	~100
0.3	<1.0	1	high[2]	81
		Conrel Formulations		
6.0	2.3	3	low[1]	73
6.0	9.0	3	low[1]	92
6.0	36.0	3	low[1]	~100
4.0	36.0	1	high[2]	77

[1]Test conducted in Oregon.

[2]Test conducted in New Mexico.

(*Z*)-6-Heneicosen-11-one is an unusual pheromone. It is relatively non-volatile and appears to be quite stable. We have recovered traps, lost the previous season and originally baited with 0.1 μg pheromone, that were still capturing fresh males 1 year later. Both Conrel fibers (Sower et al., 1979a) and the Bend Research formulations (Sower and Daterman, 1977) have easily lasted the field season with 40 to 50% of the original pheromone still present at the end.

When populations are sufficient to cause partial defoliation, we expect application of pheromone to result in about an 80% reduction in numbers of larvae the next season. This should hold damage to acceptable levels the next year and still allow natural control agents time to overtake and collapse the population before severe damage occurs. A stand that is not totally defoliated is expected to show substantial recovery (Wickman, 1979). If the population buildup was anticipated a year earlier, perhaps upwards of 90% reduction in reproduction would occur and the outbreak would be prevented. We do not know if such preventive treatment can be made cost-effective, but the ability to detect building moth populations before significant damage occurs appears feasible now (Daterman, 1978).

Low-level populations could presumably be eliminated from isolated areas with a multiple-year treatment program. A 90+% reduction each year should drive an already low population to zero. Since tussock moth dispersal is passive and probably slow reinvasion of larger areas from which the moth has been eliminated might take a long time. We do not know if this approach is economically feasible but it appears technically possible.

WESTERN SPRUCE BUDWORM

Western spruce budworm is a destructive defoliator of true firs, Douglas-fir, and spruce, Picea spp., (Furniss and Carolin, 1977). Periodic outbreaks persist for 4 to 5 years. Larvae feed on the current year's growth. Tree growth is decreased, top kill and other deformities occur, and trees are occasionally killed. Adults are active and oviposit in July and August with one generation/year.

We have conducted preliminary tests for disruption of mating of the western spruce budworm. Because results of these studies have not yet been published or concurrently submitted, collated data discussed can be made available on request. These tests are supported by the PNW Station and the Canada/U.S. Spruce Budworm Program-West.

Pheromone Identification and Disruption Tests

The pheromone is principally (E)-11-tetradecenal (Weatherston et al., 1971). Several additional materials, including the alcohol and acetate forms and the Z isomer of all of these, are also thought to be present in the females. Except for small quantities of the Z isomer of the aldehyde, however, none of these additional compounds have yet been shown to enhance attraction into traps. (E)-11-Tetradecenal was tested on small plots (20 x 20-m, 3 reps.) monitored with female-baited traps in the presence and absence of the other materials. Disruption with (E)-11-tetradecenal alone was 91% relative to checks, about equal to disruption of 84% with all of the other materials also present.

Disruption was tested on a larger scale in north central Oregon in 1979. Population densities were moderately high. Plots of 10 to 145 ha were treated (3 reps.) with 2 or 20 g of (E)-11-tetradecenal carried in 950 g of Hercon flakes/ha. Application was by aircraft.

Disruption appeared insufficient to substantially inhibit reproduction. Posttreatment egg mass samples were attempted but sample results were inadequate to document moderate amounts of disruption and no massive disruption was indicated. Female-baited traps in untreated plots captured 165 ± 91 ♂/trap. [Traps showed an 80% (33 ± 25 ♂/trap)]. Traps showed an 80% (33 ± 25 ♂/trap) reduction in males captured at 2 g/ha and 87% (22 ± 15 ♂/trap) reduction at 8 g/ha. If the average female can attract 22 to 33 males, mating is still likely even though substantial reduction occurred.

Low disruption effect was not due to any qualitative failure of materials or application. Pheromone content of flakes declined progressively until 5 to 10% of the original amount remained at the end of the adult flight (Figure 2). Of flakes found on foliage and marked just after treatment, 95% remained in place throughout the season. Disruption effect on male captures in traps was about as good at the end of the season as at the beginning. Further, trap captures at 20 m above ground were disrupted about equally to those 2 m above ground indicating a vertical treatment effect. Plastic sheets collected 59% of the intended treatment (8 ± 3 flakes/m^2) indicating good coverage. The pheromone content of individual flakes (0.2-2.0%) was lower than we have used with other species.

Disruption effects on western spruce budworm were quite low relative to results with western pine shoot borer on Douglas-fir tussock moth. High population densities were a likely contributing factor, and the insects may have been less dependent on long-range pheromone communication because of their close proximity. Higher pheromone dosages may be required, and further exploratory tests are anticipated.

SAFETY AND ENVIRONMENTAL IMPACTS

Several acute mammalian toxicity tests of pheromone compounds are done under contract before they are used in substantive field disruption tests. Costs for these tests are low with purchase of the 500 g of required pheromone being a major share of the cost. Results are well worth having during the research phase and may eventually be applicable toward registration requirements. The types of tests conducted were as follows: oral LD_{50}--rat, dermal LD_{50}--rabbit, primary skin irritation--rabbit, eye irritation--rabbit, and acute inhalation--rat. (Western pine shoot borer pheromone apparently irritated the eye of one (of several) rabbits with no other effects noted on tested animals.) Douglas-fir tussock moth pheromone and western spruce budworm pheromone had no effects on test animals.

We also were careful to watch for unexpected adverse environmental impacts which might occur. For example, host finding could involve kairomone-mediated behavior on the part of parasites. Accordingly, we are interested in any possible effect of the synthetic pheromones on parasites. Parasitization of tussock moth eggs was not reduced by pheromone application (Sower and Torgersen, 1979). Emergence of Telenomus californicus Ashmead and Tetrastichus spp. from tussock moth eggs was the same in a New Mexico plot treated with pheromone and in an adjacent untreated check plot.

RESEARCH AND DEVELOPMENT NEEDS

Interaction between effects of disruption treatments and insect population dynamics needs further study. For example, we do not know whether 95% control in 1 year is likely to be more effective than an 80% control for 3 consecutive years. Can the rise and fall of cyclic pests be monitored and predicted accurately enough to determine when prophylactic treatment is warranted? Is population density always a critical factor? Some other technical generalities require further clarification. Do dose response curves follow the log scale plot as shown in Figure 1?

The cost of pheromones can be a limiting factor in research and operational use. Prices of $3/g and upward prevent potential use of dosages much beyond 10 to 20 g of active pheromones/ha for many insects. Dosages of 100 g to 1 kg/ha (only 1.5 to 15 oz/acre!) are not really high except for price. These dosages are not getting proper research attention for field and forest pests due to cost. When females are good fliers and large plots are required to prevent inundation, high pheromone costs prevent research applications. Cheaper pheromones would remove many constraints on pheromone use.

Pheromone treatment should be considered for integrated use with other methods such as biological insecticides. Such methods alone are often not 100% effective but neither do they have severe environmental impact. We have discussed integrated uses often enough but know of no actual investigation.

SUMMARY

Control of damage by western pine shoot borer with disruption treatment has been accomplished with dosages that appear economically feasible. Larger-scale applications for control are planned, and registration appears likely.

Disruption was highly to moderately effective in reducing Douglas-fir tussock moth reproduction. Further tests stressing impact on damage and population levels are anticipated. Test results with western spruce budworm are still tentative.

We have yet to find evidence of any safety problems or significant adverse environmental impacts associated with pheromone disruption of forest Lepidoptera.

Research on disruption of appropriate forest pests should continue. Focal points could include improved methods for applying and using materials and cost reduction. Relevant studies of insect population dynamics are welcomed. Possibilities for integration with other methods of insect control should be explored.

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