United States
Department of
Agriculture

Forest Service

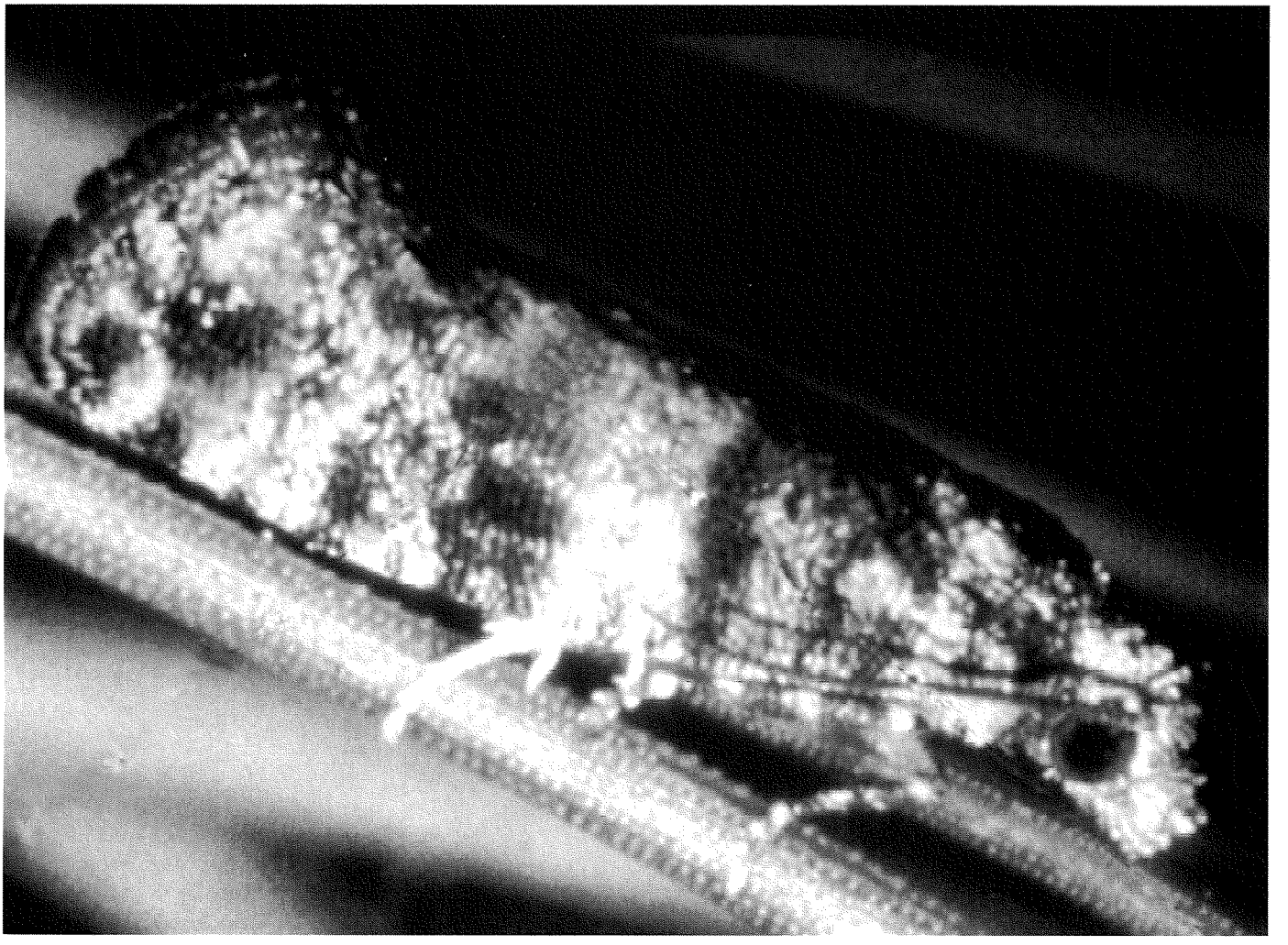
Southern
Research Station

General Technical
Report SRS–51

The Nantucket Pine Tip Moth: Old Problems, New Research

Proceedings of an Informal Conference The Entomological Society of America, Annual Meeting

Atlanta, Georgia
December 12–16, 1999



Cover: Nantucket pine tip moth adult.

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June 2002

Southern Research Station
P.O. Box 2680
Asheville, NC 28802

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Edited by

C. Wayne Berisford, Professor
Department of Entomology
University of Georgia
Athens, GA 30602–2603, USA

Donald M. Grosman, Entomologist II
Texas Forest Service
Cudlipp Forestry Center
P.O. Box 310
21127 South First Street
Lufkin, TX 75902–0310, USA

Sponsored by

The University of Georgia
USDA Forest Service, Southern Research Station

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PREFACE

The Nantucket pine tip moth is an enigmatic insect whose perceived importance as a pest has waxed and waned through the years. Although it rarely kills trees, attacks by the moth kill growing shoots and can cause growth loss and poor form. The moth has been the subject of a considerable amount of research at times and has almost been ignored during other periods. For example, there was a spate of research during the late 1950's and 1960's when large acreages were converted from agriculture to pine plantations. After that period, there appeared to be little interest in the moth during the 1970's and 80's. However, another round of conversions from agriculture to pine plantations occurred via the Federal Conservation Reserve Program in the 1980's and 90's. Also, the concomitant development of intensive plantation management which included intensive mechanical site preparation, herbicide applications to control competing vegetation and fertilization, apparently exacerbated tip moth infestations and created renewed interest in research.

The most recent peak of interest led to the formation of the Pine Tip Moth Research Consortium which combined resources from several public and private institutions to provide funding and bring expertise to bear on the problems caused by tip moth infestations in intensively-managed stands. The initial idea for the Consortium was developed by F. S. Broerman, Union Camp Corporation and Steven A. Cade, Weyerhaeuser Company. The Pine Tip Moth Research Consortium had six industrial members when it was initiated in 1995-96 including: Champion International Corporation, Georgia Pacific Corporation, International Paper Corporation, Jefferson Smurfit Corporation, Union Camp Corporation and Weyerhaeuser Company. The USDA Forest Service was also a member via the Forestry Sciences Lab, Research Work Unit No. 4505 based in Athens, Georgia. The Consortium was administered through the University of Georgia with participation by the Department of Entomology and the Warnell School of Forest Resources. The program was directed by C. W. Berisford, Department of Entomology. In addition to voting members, there were several associate industrial members of the Consortium who made financial contributions and provided materials for direct tip moth control evaluations. Associate members included Abbott Laboratories, American Cyanamid Company, Bayer Corporation, Dow AgroSciences LLC, Gowan Company, Rohm & Haas Company, Valent U. S. A. Corporation and Zeneca Ag Products.

Additional resources were provided by the Georgia Traditional Industries Program in Pulp and Paper (TIP^3) via competitive grants and the USDA Forest Service as cooperative agreements through the Forest Health Technology Enterprise Team, Morgantown, West Virginia and a Special Technology Development Project sponsored by Forest Health Management, Region 8, Atlanta, Georgia. Other institutions which provided resources and/or expertise were: Clemson University (Dr. Roy L. Hedden), The Texas Forest Service, Pest Control Section (Dr. Donald Grosman), Auburn University (Dr. J. Wayne Brewer).

Through the efforts of the Consortium members and their cooperators, a body of new information regarding the biology and control of the tip moth was developed. In conjunction with the Entomological Society of America annual meeting, an Informal Conference was held on December 13, 1999 to review some new research and to provide a forum for discussions of future research.

We sincerely appreciate the help and advice of Mr. Jimmy Seckinger, International Paper Corporation on various field projects. We are grateful to Dr. Kerry Britton, USDA Forest Service, Southern Research Station for sponsoring publication of these proceedings.

EXECUTIVE SUMMARY

The Nantucket pine tip moth has become a more prevalent pest as the intensity of pine plantation management has increased. Because some forest product producers feel that growth losses due to tip moth attacks may be unacceptable, the Pine Tip Moth Research Consortium was formed to increase basic knowledge about the moth and to explore ways to reduce tip moth damage. A conference was held in 1999 to highlight some research supported by the consortium and other institutions. Research has been conducted on damage assessment (impact), interactions of the moth with different forest management practices, effects of herbicide and insecticide use on tip moth parasitoids, evaluations of insecticides for tip moth control, optimizing chemical control through more precise timing, potential for augmenting tip moth egg parasites, pheromone traps to predict tip moth infestation density and tests of different pheromone trap designs and lures.

Models were developed to relate tree growth to tip moth infestation levels. Tip moth attacks were found to have their greatest effect on tree height growth during the early generations in each growing season in the first three years following stand establishment.

Tip moth infestation levels increased as management intensity increased, particularly in regard to control of competing vegetation. Tip moth populations appeared to be less stable in plots with the highest management intensity, ranging from epidemic levels to almost no infestation over 10 consecutive generations..

Tests of various insecticides showed that a wide variety of insecticide types and formulations could provide effective tip moth control. Some insect growth regulators showed considerable promise for tip moth control with minimal impact on natural enemies. It appears that there will be a variety of insecticides available for tip moth control in the future since most of the compounds tested are also labeled for use on major agricultural crops.

Effective tip moth control with insecticides is highly dependent on proper timing. Several timing techniques have been developed over the years and are briefly reviewed. A new method is described which uses historical temperature data from a grid of weather stations to predict optimum times for chemical control of each tip moth generation in areas with three or four generations annually.

Studies of interactions among tip moth parasitoids, herbicides and insecticides showed that overall parasitism was not affected by herbicidal control of competing vegetation although the relative contribution of some parasitoids was changed. Parasitism was reduced by certain broad spectrum insecticides but not all of the parasitoids were affected equally with some species apparently unaffected while others were virtually eliminated. It appears that pesticides for tip moth control and parasitoids can be compatible if insecticides are selected to minimize impact on these natural enemies.

Experimental releases of the native tip moth egg parasite *Trichogramma exiguum* showed that there may be some potential for augmentative releases of lab-reared parasites. Impact evaluations showed that the egg parasites reduced larval populations by 60 percent. Although the percentage of tip moth-infested shoots was not different from those in untreated check plots, the amount of damage to infested shoots was significantly reduced due to fewer larvae per shoot. *Trichogramma* survival was higher in areas in which some vegetation had been retained between rows of planted pines.

Traps baited with synthetic pheromone lures have been used to monitor tip moth activity and to help with timing of control attempts. In the past, it was assumed that trap catches of male tip moths did not relate to populations and therefore could not be used to estimate population density. However, by standardizing traps and baits, plus correcting for differential male longevity during different generations, it may be possible to make reasonably accurate population estimates. Additionally, a method has been developed to predict damage based on catches of moths from the previous generation.

Although pheromone-baited traps have been used to monitor tip moth activity, time insecticide applications and may be used in the future to quantify populations or predict damage, there is no "standard" trap or pheromone bait. Workers have been using a variety of systems which do not allow comparisons of information gathered by trapping. There are a number of commercially available baits and traps, but they have not been compared. Several traps and lures were tested to determine which were the most effective and consistent for catching tip moths. Pherocon 1C^{R} wing traps consistently caught more moths, but most designs caught moths at the same time at the beginning of moth emergence. Several available lures worked well but were effective for different lengths of time.

INTRODUCTION

The Nantucket pine tip moth, *Rhyacionia frustrana* (Comstock) (Lepidoptera: Tortricidae), is one of the most common forest insects in the Southeastern United States (Berisford 1988). Although it is usually considered to be a southern pest, the range of the moth includes much of the eastern half of the United States, southern Mexico and Central America (Powell and Miller 1978). It is also established in southern California and parts of Arizona and New Mexico where it was accidentally introduced.

Most hard pines are susceptible to attack by *R. frustrana*, but there are considerable differences in relative susceptibility. For example, among the southern pines, shortleaf (*Pinus echinata* mill.), loblolly (*P. taeda* L.), and Virginia pines (*P. virginiana* Mill.) are highly susceptible, while slash pine (*P. elliottii* Engelm.) is highly resistant and longleaf pine (*P. palustris* Mill.) is virtually immune to attack with the exception of very young nursery seedlings. Monterey pine (*P. radiata* D. Don), is highly susceptible in the introduced range in southern California (Scriven and Luck 1978) and ponderosa pine (*P. ponderosae* Douglas ex. Laws.) is frequently attacked in Arizona and New Mexico.

The natural range of *R. frustrana* in the United States overlaps with at least three other common species of *Rhyacionia*. Its most common associate, the pitch pine tip moth, *R. rigidana* (Fernald), often shares the same hosts (Baer and Berisford 1975, Miller and Wilson 1964) and at least some of their life stages overlap (Berisford 1974, Canalos and Berisford 1981). The range of *R. frustrana* overlaps to a lesser degree with that of the subtropical pine tip moth, *R. subtropica* Miller, and an introduced species, the European pine shoot moth, *R. buoliana* (Schiffermuller) (Powell and Miller 1978).

Damage caused by *R. frustrana* may be serious, resulting in severe stunting and stem deformation, and, in extreme cases, death of the host (Yates and others 1981). However, damage is often transitory or negligible in many forest stands. The reasons for radically different tip moth populations and/or damage in different stands are not fully understood, but they appear to be at least partly related to tree species, site quality, natural enemies, and competing vegetation. The latter is often a function of the intensity of site preparation prior to planting and/or the use of herbicides to control competing vegetation.

Tip moth damage is most severe on seedlings and saplings, usually under 5 years old, and is usually manifested as growth loss and/or loss of tree form. The excessive branching and competition among lateral limbs for dominance following heavy attacks can result in significant increases in compression wood and loss of wood quality (Hedden and Clason 1980). Form loss is particularly important on ornamentals and Christmas trees, which may become virtually worthless if tip moth attacks are not controlled. The long term impact of *R. frustrana* attacks, particularly on tree height growth, is controversial. Some studies show permanent losses, some indicate temporary losses that are regained, and others show no effect. Cade and Hedden (1987) showed long-term growth losses in Arkansas and reviewed the literature pertaining to tip moth impact.

Within the natural range of *R. frustrana,* the life cycle is synchronized with its primary hosts to produce a new generation of egg-laying adults when a new growth flush begins. This synchrony provides larvae with soft, nutritious meristematic tissue in which to feed during their early development. The moth has two to five generations annually, depending on the climate. Generations are usually discernible, but considerable overlap may occur after mid-summer, even in areas with as few as three annual generations (Gargiullo and others 1984, Fettig and Berisford 1999). The moth overwinters as pupae within shoots that have been killed by larval feeding. Development occurs above a threshold of 9.5°C (Haugen and Stephen 1983), and adults may emerge in late December or January in the southern part of its range. Adults are normally crepuscular, but late afternoon flights may occur preceding evening temperatures that fall below the flight temperature threshold of 10°C. This early flight behavior is apparently triggered by daytime temperatures just above the threshold (Webb and Berisford 1978). Males begin to emerge before females and large numbers are often present when the first females appear (Berisford and Brady 1972). Mating is mediated by a sex pheromone (Berisford and Brady 1972). Two pheromone components have been identified as (E)-9-dodecenyl acetate and (E)-9, 11-dodecadienyl acetate (in a ratio of 96: 4) (Hill and others 1981). *Rhyacionia frustrana* responds weakly to the pheromones of *R. subtropica* and *R. buoliana*, but neither of these species are attracted to *R. frustrana* (Berisford and others 1979).

Mating occurs shortly after emergence, and eggs are deposited on shoots and needles. Females oviposit almost exclusively on highly susceptible hosts such as loblolly pine even when they are adjacent to resistant hosts such as slash pine (Hood and others 1985). The first visible evidence of tip moth attack is often small drops of resin exuding from needle bases, where first instar larvae have begun to feed. Second instars feed at needle or bud axils where they construct a characteristic silk tent which becomes covered with resin. Subsequent instars feed inside buds and shoots, and fully grown larvae pupate inside the dead shoots (Yates and others 1981). Multiple infestations are common with up to 15 individuals per shoot, depending on population density and shoot diameter.

Rhyacionia frustrana has a substantial complement of parasitoids and predators (Eikenbary and Fox 1965). Most data on natural enemies have come from mass rearings from tip moth-infested shoots, but a few studies have attempted to more precisely determine the roles of the associated arthropods. Fourteen species of insects and seven spiders have been observed to prey on the tip moth

in the field and laboratory (Eikenbary and Fox 1968a). No estimates of impact were made in studies by Eikenbary and Fox, but spiders were the most abundant predators during the summer, and two species of clerid beetles *(Phyllobaenus* spp.) were apparently most important during the spring (first) generation. Although there are a number of parasitoids associated with *R. frustrana*, including 26 Hymenoptera and one Diptera species (Warren 1985), only a few appear to be sufficiently abundant to have significant impact on tip moth populations. Parasitoids from individual *R. frustrana* larvae and pupae have been reared to help determine their specific parasitic roles, particularly those species reported to be cleptoparasites and hyperparasites (Freeman and Berisford 1979). One of the more abundant species found in rearings *((Eurytoma pini* Bugbee (Hmenoptera: Eurytomidae)) is primarily cleptoparasitic (i.e., attacking only previously parasitized larvae), although it may also be a primary parasitoid or hyperparasitic. However, conditions under which it is a primary or a secondary parasitoid are unknown. Most studies on larval and pupal parasites have shown that the ichneumonid wasp, *Campoplex frustranae* Cushman, and the tachinid fly, *Lixophaga mediocris* Aldrich, were the most abundant. They constituted 23 and 45 percent of all parasitoids, respectively, when averaged over four generations in Georgia (Freeman and Berisford 1979). However, *C. frustranae* was absent from samples of 8 consecutive generations in the Georgia coastal plain (McCravy and Berisford 2000). The next most abundant parasitoids were *Eurytoma pini* (11 percent) and *Perilampus fulvicornis* Ashmead (Eupelmidae) (6 percent) . The role of *P. fulvicornis is* unclear, as it appears to function both as a primary parasite and as a hyperparasite.

Egg parasites *(Trichogramma* spp.) appear to be important in regulating tip moth populations, with up to 64.5 percent of the eggs being parasitized (Yates 1966). Egg parasitism was heavier in summer than in the spring generation, in two studies in the Georgia Piedmont Plateau (Gargiullo and Berisford 1983, McCravy and Berisford 1998). Lower egg parasitism in the first generation could be due to poor survival of overwintering *Trichogramma* wasps or to the presence of many alternate hosts in the spring. Overall egg mortality was also found to be density-dependent, and most of this morality was due to *Trichogramma* parasitism (Gargiullo and Berisford 1983). By contrast, no evidence of density-dependent responses has been observed among larval and pupal parasitoids (Eikenbary and Fox 1968b).

Life table studies showed that most tip moth mortality occurred during the egg, late larval, and pupal stages (Gargiullo and Berisford 1983). Egg mortality was mostly due to *Trichogramma spp.,* while considerable pupal mortality was caused by *C. frustranae. Campoplex frustranae* was released into introduced *R. frustrana* infestations in California where it significantly reduced tip moth damage (Scriven and Luck 1978).

The abundance of *R. frustrana* is strongly affected by the availability of preferred hosts which are in susceptible age classes (usually 1-5 years). Plantations are capable of producing large populations within one year of establishment. Colonization of pine plantations is often rapid, with initial infestations being random but becoming clumped in later generations (Clarke 1982). Peak infestations usually occur 2-4 years after establishment when population levels are positively correlated with the number of available shoots (Lashomb and others 1980). Although the number of available shoots increases with time and tree height, the proportion of shoots infested declines, suggesting that other factors such as host resistance, asynchrony of growth flushes and moth emergence or parasitism, may reduce the success of the moth as trees become older.

The highest tip moth numbers and damage tend to occur in even-aged stands with little competing vegetation and/or low vegetation diversity. For example, plantations in old fields generally have higher infestations than do natural stands with the same average spacing (Berisford and Kulman 1967). Several studies have shown increased tip moth infestations concomitant with decreases in amount and/or diversity of competing vegetation (Hertel and Benjamin 1977, Hood and others 1988, Miller and Stephen 1983, Ross and others 1990b, Warren 1963, White and others 1984). Intensive stand management techniques which normally include mechanical site preparation, herbicides and fertilizer, increase tree growth but may also increase tip moth damage. These practices may, among other things, decrease the availability of alternate hosts and other food sources such as pollen and nectar, for natural enemies.

Site quality may also affect tip moth populations and/or damage. Poor sites had higher tip moth populations in the Piedmont Plateau region in the Southern U.S., with site index being negatively correlated with tip moth infestations (Hood and others 1988). However, high tip moth populations were found to be associated with higher site indices in Texas (White and others 1984). Specific soil characteristics, such as texture, depth of "A" horizon, calcium content, pH, and percentage and/or depth of clay, were correlated with infestation levels, but site index and soil calcium accounted for much of the variation in the Piedmont Plateau. Although there are no definitive data on the effects of site quality on resistance to tip moth attack, it seems likely that root establishment is faster on better sites, thereby increasing the general health of the seedlings. Some resistance is apparently due to high resin flow (Yates 1962) or perhaps to induced hypersensitive reactions, such as that often associated with bark beetles (Raffa and Berryman 1983). High nutrient levels which produce healthy trees may also provide some measure of protection via tolerance to tip moth attacks. Ross and Berisford (1990) found that loblolly pine seedlings which had received high levels of nutrients and water supported higher tip moth populations, but suffered proportionately less damage than trees receiving low nutrients and water even though those trees had lower infestations. Rapid growth provided by good sites also reduces the period during which trees are highly susceptible, since infestation generally decreases with tree height and age.

Methods for detection of *R. frustrana* are diverse but there is no "standard" methodology. Pheromone traps are often employed to determine when tip moth emergences occur,

but no trap catch—damage thresholds have been established. Pheromone traps are usefully employed for timing of insecticide applications for tip moth control (Gargiullo and others1985). It appears that most detection methods rely on simply looking for evidence of damage, usually dead shoots, and confirming that a tip moth infestation exists. Most observers apparently assume that infestations are *R. frustrana,* although there may be other species present as previously mentioned.

Methods for damage evaluation are mostly based on numbers of infested shoots per tree or percentage of available shoots infested. However, there are currently no guidelines by which damage (growth loss) may be predicted by counts of infested shoots. Reliable sampling methods have been developed for determination of tip moth populations on a shoot, tree, or area (hectare) basis (Gargiullo and Berisford 1981, Gargiullo and others 1983). However, the necessary links between population estimates and damage predictions have not yet been established. Although it may seem surprising that damage prediction methods or damage thresholds for *R. frustrana* have not been developed, it might be expected in light of the previous contradictory information regarding transitory vs permanent damage.

Rhyacionia frustrana infestations in pine plantations have generally been regarded as inevitable and uncontrollable. Since tip moths rarely kill trees, and their impact on volume and form is highly variable, management has generally been focused on maintaining stand vigor through appropriate silvicultural treatments in both natural and plantation forests. As the acreage of intensively managed pine plantations has increased to maximize fiber and timber production on a shrinking land base, *R. frustrana* has emerged as a more serious and persistent pest problem.

A system for managing *Rhyacionia frustrana* in pine plantations would likely include the following components: 1) a hazard-rating system to make pre-established predictions of potential damage, 2) practical survey techniques to determine current population levels, 3) economic thresholds, or action thresholds, to trigger the use of direct control activities, 4) safe and effective insecticides 5) models to assist with proper timing of insecticide treatments, 6) genetically resistant planting stock, 7) cultural practices that reduce tip moth populations and/or their damaging effects on pines, and 8) techniques for augmenting the effectiveness of natural control agents. Only a few of these components have been thoroughly investigated or are currently used in forest plantation management.

A substantial body of information has been accumulated on *R. frustrana* biology and control through many years of study. However, this research has been fragmented and generally uncoordinated and considerable additional work will be required to eventually develop integrated pest management programs. With the widespread adoption of intensive forest management, highly visible tip moth damage has increased interest in research on *Rhyacionia* species, especially *R. frustrana*. More comprehensive work with well-defined objectives, structure, and linkages with forest management systems is essential. The Pine Tip Moth Research Consortium was formed in 1995 to conduct research on tip moth problems associated with intensively managed loblolly pine plantations. The Consortium, based at the University of Georgia, Department of Entomology, consisted of six forest companies, The U. S. Forest Service and The University of Georgia. The primary areas targeted for investigation by the Research Consortium included: impact, improved insecticidal control, natural enemies, effects of cultural treatments, population and damage estimates and evaluations of pheromone lures and traps.

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IMPACT OF PINE TIP MOTH ATTACK ON LOBLOLLY PINE

Roy Hedden[1]

Abstract—Data on the impact of Nantucket pine tip moth, *Rhyacionia frustrana,* attack on the height of loblolly pine, *Pinus taeda,* in the first three growing seasons after planting from three locations in eastern North Carolina (U.S.A.) was used to develop multiple linear regression models relating tree height to tip moth infestation level in each growing season. These models were used to demonstrate which tip moth generations cause significant damage to the tree, thus facilitating the identification of generations that are good candidates for tip moth control. The height impact models were also used to calibrate a pine growth model to estimate volume loss associated with tip moth attack. Lastly, an example of how to use the information on volume impact to economically evaluate a potential pine tip moth control program is presented.

INTRODUCTION

Over 12 studies documenting some aspect of pine tip moth impact have recently been reviewed and summarized (Hedden 1998). However, none of these studies contain detailed information on the relationship between tip moth infestation level and tree growth. Most of the studies consist of one or more locations where there were a group of plots, half of which received some form of tip moth control while the other half received no treatments. Also, many of them described tip moth infestation in qualitative terms, or only measured tip moth level once during the year, usually for the overwintering generation. Consequently, these studies are not useful for developing models relating tip moth infestation levels to growth impact of the tree. However, such models are needed to predict long term impact of tip moth attack on pine growth, and to evaluate the economic feasibility of developing a pine tip moth control program.

The purpose of this paper is to present models relating Nantucket pine tip moth infestation levels to loblolly pine growth. In addition, we will show how these models can be used to estimate long-term impact of tip moth attack on pine yield, and how this information can be used to make decisions about a pine tip moth control program.

METHODS

Field plots were installed in three locations in eastern North Carolina in 1985 and 1986 to evaluate loblolly pine for tip moth resistance (Cade and Hedden 1989). All locations had moderate to high organic soils; planting sites were drained, intensively site-prepared by piling and burning the residual slash, and bedded. An aerial application of sulfometuron methyl for herbaceous weed control was applied to all sites in May of the year of planting. One location (LOC2) was installed in 1985, and two (LOC1 and LOC3) in 1986. One-year-old nursery seedlings from half-sib families were planted in replicated plots in March. Families included in the study were from genetically improved parents, and were well represented in operational plantings in the area. Five pine families were common to all three sites. The experimental design was randomized block with split plots. At each location, either 36-tree plots with three blocks (1985) or 24-tree plots with four blocks (1986) were installed. All trees in a given plot were of the same family, i.e., one plot per family.

The plots were split with one-third of the trees on each plot receiving insecticide treatments to protect them from pine tip moth attack. The study site established in 1985 received the insecticide treatment in the second (1986) year only; at the other two locations, insecticide treatments were applied in both 1986 and 1987. The first-year insecticide treatment consisted of 0.5 g active ingredient (AI) of carbofuran granules applied to each seedling at the time of planting. Second-year insecticide applications consisted of one of the following: (1) carbofuran granule application at a rate of 5 g AI per cm of basal diameter per tree incorporated into the soil at the base of the tree, or (2) foliar applications of fenvalerate timed to coincide with each tip moth generation.

Tree heights were measured at the beginning of each growing season and at the end of each tip moth generation—late June, early August, and October. Basal diameter was measured at the beginning of the growing season and at the end of the growing season in 1987. The number of growth flushes during the growing season was also recorded for each tree. Tip moth infestation level was recorded at each measurement period in the first growing season by recording the infestation status of the terminal bud only. Thereafter, the number of infested and uninfested buds in the terminal whorl of branches immediately below the terminal bud was also recorded. Data were collected for the first and second years for the two sites established in 1986. Data were collected in the second and third year for the site installed in 1985.

The data from the sites was grouped by growing season [two first-year sites (LOC2 and LOC3), three second-year sites (LOC1, LOC2 and LOC3) and one third-year site (LOC1)]. The relationship between tip moth infestation level and tree height was modeled using stepwise multiple linear regression (SAS 1988). Data from individual trees were used in all analyses for the five pine families common to all three sites. Two sets of models were developed for each growing

[1] Department of Forest Resources, Clemson University, Clemson, SC 29634-1003, rhddn@clemson.edu.

Citation for proceedings: Berisford, C. Wayne; Grosman, Donald M., eds. 2002. The Nantucket pine tip moth: old problems, new research. Proceedings of an informal conference, the Entomological Society of America, annual meeting. 1999 December 12–16. Gen. Tech. Rep. SRS–51. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 68 p.

season—a full model containing information on site, family, treatment, initial tree height and infestation level, and a reduced model consisting of initial tree height and infestation level were generated for each growing season.

Dummy categorical regressors were used to express several variables. Insecticide treatment (TRT) was coded as 1 for treatment and 0 for no treatment. Two variables (SITE1 and SITE2) were used to code sites—SITE1 was 1 for LOC1 and 0 for LOC2 and LOC3, and SITE2 was 1 for LOC2 and 0 for LOC1 and LOC3. Four categorical variables (FAM1, FAM2, FAM3 and FAM4) were used, in a manner similar to the site variables, to express the five pine families. All dummy regressors for either the site or family variable were included if at least one of the individual dummy variables was found significant.

Yield information for loblolly pine was generated from the whole stand equations of Burkhart and others (1972). Total cubic feet inside bark and cords of pulpwood to a four-inch top were for unthinned stands with a site index of 70 (base age 25) at age 15. Tip moth impact was simulated by reducing the average height of the dominant and codominant trees in the stand. A stumpage value of $30 per cord was used in calculating the present value of Nantucket pine tip moth attack (Timber Mart-South 1997). English units will be used when discussing pine yield because these are the units in the timber trade in the U.S.

RESULTS AND DISCUSSION

Seasonal Tree Height Models

The full model for estimating loblolly pine height undergoing Nantucket pine tip moth attack in a specified year is:

$$HT = b_0 + b_1\ IHT + b_2\ FLUSH + b_3\ SITE1 + b_4\ SITE2 + b_5\ FAM1 + b_6\ FAM2 + b_7\ FAM3 + b_8\ FAM4 + b_9\ TRT + b_{10}\ TI1 + b_{11}\ TI2 + b_{12}\ TI3 + b_{13}\ PBI1 + b_{14}\ PBI2 + b_{15}\ PBI3$$

where

HT = tree height at the end of the growing season (cm)
FLUSH = number of growth cycles during the growing season
IHT = tree height at the beginning of the season (cm)
SITE1 = dummy variable for location (0 or 1)
SITE2 = dummy variable for location (0 or 1)
FAM1 = dummy variable for family (0 or 1)
FAM2 = dummy variable for family (0 or 1)
FAM3 = dummy variable for family (0 or 1)
FAM4 = dummy variable for family (0 or 1)
TRT = dummy variable for insecticide treatment (0 or 1)
TI1 = terminal infestation in generation 1 (0 or 1)
TI2 = terminal infestation in generation 2 (0 or 1)
TI3 = terminal infestation in generation 3 (0 or 1)
PBI1 = percent buds infested in the top whorl in generation 1
PBI2 = percent buds infested in the top whorl in generation 2
PBI3 = percent buds infested in the top whorl in generation 3

The results of the stepwise regression for the first growing season are shown in Table 1. Initial tree height at planting and the number of growth flushes had a strong positive effect on seasonal height growth. There were also significant differences between location, family and treatment. Tip moth infestation level had a significant negative effect on tree

Table 1—Full and reduced regression models for predicting total tree height (cm) of loblolly pine during the first growing season

		Full Model[b]		Reduced Model[c]	
Variable[a]	i	Regression Coeff. (b_i)	Prob. Value	Regression Coeff. (b_i)	Prob. Value
CONSTANT	0	11.0248	0.0001	54.5492	0.0001
IHT	1	0.8736	0.0001	0.6598	0.0001
FLUSH	2	8.5571	0.0001		
SITE1	3	4.2425	0.0001		
FAM1	4	1.0063	0.3640		
FAM2	5	0.4197	0.7181		
FAM3	6	-3.1253	0.0055		
FAM4	7	1.0411	0.3419		
TRT	8	7.0248	0.0001		
TI1	9	-10.3407	0.0001	-26.2401	0.0001
TI2	10	-3.3799	0.0001	-8.3746	0.0001
TI3	11			-5.3157	0.0001
R^2		0.61		0.24	
Sy.x		10.5		14.6	
N		936		936	

[a] IHT is the initial tree height (cm); FLUSH is the number of annual growth flushes; SITE1 is location (0 or 1); FAM1, FAM2, FAM3 and FAM4 is the pine family (0 or 1); TRT is the insecticide treatment (0 or 1); TI1, TI2 or TI3 are the tip moth infestation of the terminal (0 or 1) in generation 1, 2 or 3.
[b] $HT = b_0 + b_1\ IHT + b_2\ FLUSH + b_3\ SITE1 + b_4\ FAM1 + b_5\ FAM2 + b_6\ FAM3 + b_7\ FAM4 + b_8\ TRT + b_9\ TI1 + b_{10}\ TI2 + b_{11}\ TI3$
[c] $HT = b_0 + b_1\ IHT + b_9\ TI1 + b_{10}\ TI2 + b_{11}\ TI3$

height in the first two tip moth generations. Loss of height was greatest for attack in the first generation and least for the second. Since infestation level was coded only as terminal infestation in the first growing season, there was no possibility for the percent infested buds in the top whorl to be included in the regression model. Also, only SITE1 is included in the full model since there were just two locations for the first growing season. The model R^2 of 0.61 was quite high for predicting height growth during the first year considering that these seedlings were suffering from transplant shock and they were in adapting to the site. It should be noted that there was significant positive height growth associated with the insecticide treatment that was apparently not related to tip moth attack. There are many insects that feed on young loblolly pine in addition to Nantucket pine tip moth (Drooz 1985). Consequently, any broad-spectrum insecticide application to control tip moth will provide some growth enhancement from the control of nontarget pests.

The reduced model for the first growing season only includes initial tree height and tip moth infestation level (table 1). In this case, tip moth attack in all three generations had a significant negative impact on tree height. However, the impact suffered in the second and third generations is much lower than that occurring in generation one. This is important since tip moth damage in the first generation is easier to control than in the later generations. An insecticide applied to the seedlings in the nursery would provide control for the first tip moth generation. Cost of applying insecticides to seedlings after planting is much more expensive.

Table 2 shows the results for the second growing season. Initial tree height at planting and the number of growth flushes had a strong positive effect on seasonal height growth. There were also significant differences between location, family and treatment. Tip moth infestation level had a significant negative effect on tree height in all three tip moth generations. Height reduction was greatest for the first moth generation and least for the third. Both terminal and first whorl infestation significantly affected tree height. The R^2 of 0.71 indicates a good fit of the model to the data.

The reduced model including only the variables for infested terminals is also presented. This model explains about 58 percent of the variation in the data (R^2=0.58). This model also shows that tip moth infestation in the first two moth generations has the greatest impact on tree height.

Table 3 shows the results for the third growing season. The full model explained about 82 percent of the variation in the data (R^2=0.82). There were significant differences between families. Initial tree height and the number of annual growth flushes were positively related to tree height. Tip moth attack

Table 2—Full and reduced regression models for predicting total tree height (cm) of loblolly pine during the second growing season

		Full Model[b]		Reduced Model[c]	
Variable[a]	i	Regression Coeff. (b_i)	Prob. Value	Regression Coeff. (b_i)	Prob. Value
CONSTANT	0	65.9368	0.0001	100.2011	0.0001
IHT	1	1.4355	0.0001	1.5397	0.0001
FLUSH	2	9.6174	0.0001		
SITE1	3	-14.1900	0.0001		
SITE2	4	-15.3390	0.0001		
FAM1	5	-7.5867	0.0001		
FAM2	6	3.2094	0.0865		
FAM3	7	-4.7245	0.0101		
FAM4	8	-1.7952	0.3260		
TRT	9	8.0130	0.0001		
TI1	10	-7.7853	0.0001	-15.9917	0.0001
TI2	11	-4.8312	0.0002	-9.1509	0.0001
TI3	12	-3.9598	0.0026	-5.5261	0.0002
PBI1	13	-0.0674	0.0013		
PBI2	14	-0.0613	0.0017		
PBI3	15	-0.0420	0.0353		
R^2		0.71		0.58	
Sy.x		20.4		24.8	
N		1254		1258	

[a] IHT is the initial tree height (cm); FLUSH is the number of annual growth flushes; SITE1 and SITE2 are location (0 or 1); FAM1, FAM2, FAM3 and FAM4 is the pine family (0 or 1); TRT is the insecticide treatment (0 or 1); TI1, TI2 or TI3 are the tip moth infestation of the terminal (0 or 1) in generation 1, 2 or 3; PBI1, PBI2, and PBI3 are tip moth infestation in the top whorl (%) in generation 1, 2, or 3.

[b] $HT = b_0 + b_1\ IHT + b_2\ FLUSH + b_3\ SITE1 + b_4\ SITE2 + b_5\ FAM1 + b_6\ FAM2 + b_7\ FAM3 + b_8\ FAM4 + b_9\ TRT + b_{10}\ TI1 + b_{11}\ TI2 + b_{12}\ TI3 + b_{13}\ PBI1 + b_{14}\ PBI12 + b_{15}\ PBI3$

[c] $HT = b_0 + b_1\ IHT + b_{10}\ TI1 + b_{11}\ TI2 + b_{12}\ TI3$

Table 3—Full and reduced regression models for predicting total tree height (cm) of loblolly pine during the third growing season

		Full Model[b]		Reduced Model[c]	
Variable[a]	i	Regression Coeff. (b_i)	Prob. Value	Regression Coeff. (b_i)	Prob. Value
CONSTANT	0	68.7594	0.0001	93.1082	0.0001
IHT	1	11.1909	0.0001	1.2017	0.0001
FLUSH	2	7.1798	0.0001		
FAM1	3	2.0258	0.5811		
FAM2	4	-7.3505	0.0609		
FAM3	5	-1.2501	0.7261		
FAM4	6	-2.2580	0.5323		
TI1	7	-8.7146	0.0010	-11.3788	0.0001
PBI1	8	-0.0478	0.1608		
R^2		0.82		0.80	
Sy.x		20.6		21.5	
N		326		326	

[a] IHT is the initial tree height (cm); FLUSH is the number of annual growth flushes; FAM1, FAM2, FAM3 and FAM4 is the pine family (0 or 1); TI1 is the tip moth infestation of the terminal (0 or 1) in generation 1; PBI1 is tip moth infestation in the top whorl (%) in generation 1.

[b] $HT = b_0 + b_1\ IHT + b_2\ FLUSH + b_3\ FAM1 + b_4\ FAM2 + b_5\ FAM_3 + b_6\ FAM4 + b_7\ TI1 + b_8\ PBI1$

[c] $HT = b_0 + b_1\ IHT + b_7\ TI1$

of the tree in the first tip moth generation had a significant negative impact on tree height. Attack during the second and third generation had no negative effect on height. Trees during this growing season are approaching the 3 meter height threshold above which they normally escape significant attack by the Nantucket pine tip moth. Once the tree reaches three meters impact by this pest declines, probably because moth attack no longer significantly reduces potential leaf area of the plant, and because the growth phenology of tree is changing from the juvenile to the mature phase (Berisford 1988).

The reduced models for relating tree height to moth infestation level in the first generation is shown in table 3. This model explains about 80 percent of the variation in the data (R^2=0.80).

Linking Seasonal Tree Height Models

The individual seasonal height growth models can be linked to investigate the effect of infestation level in a particular tip moth generation on loblolly pine height. This procedure uses the model for the first year to generate the initial height for the second year, and then uses the model for the second year to obtain the initial height for the third year. Furthermore, if values for 0 percent infestation level are substituted in each model then the tree height in the absence of tip moth attack (UHT) is obtained. Conversely, if values for 100 percent infestation level are substituted in each model then the tree height in the presence of complete tip moth attack is obtained. The difference between these two values is the maximum potential height reduction due to tip moth attack (DHT). The relative impact of tip moth attack on tree height (RI) can then be expressed as (UHT - AHT)/DHT where AHT is the estimated tree height under some specified level of tip moth attack. Values of RI can vary from 0 (no attack) to 1 (complete attack).

An example will illustrate. The reduced model using only terminal infestation will be used for all three growing seasons. If tree height at planting (IHT) was 15.5 cm, the maximum tree height (HT) without tip moth attack at the end of the first growing season will be 64.8 cm. This value is then used for the value of IHT in the second growing season, and the end-of-season value obtained for HT (200.1 cm) is used for IHT in the third season. Total height at the end of the third season (333.3 cm) represents potential tree height in the absence of tip moth attack (UHT). Total tree height at the end of the third season under complete attack for all generations would be 284.8 cm. Therefore, DHT = 333.3 - 284.8 = 48.5 cm, and RI = (333.3 - AHT)/48.5.

Now, using the same model and initial tree height at planting, and setting the value of terminal infestation to one and calculating tree height at the end the third year can assess the potential impact of a tip moth generation in any one of the three years. This value is then used to calculate the RI for a given tip moth generation. Table 4 shows the relative impact on tree height for each tip moth generation. Results for the unweighted full and reduced models clearly indicate that the greatest potential impact on tree height is caused by attack during the first generation of each year. Attack in the first generation just after planting is especially harmful. This is not surprising since the tree is suffering from transplant shock and it is adapting to the site. Furthermore, the tree has only a very small leaf area at this time and anything that interferes with the development of new foliage will severely delay the growth of the seedling. Indeed, trees in this study with infested terminals only in the first

Table 4—Relative impact of pine tip moth attack (RI) and RI weighted by observed infestation level for each generation and growing season

Year	Unweighted (RI) Moth gen.	Unweighted (RI) Full model	Reduced model	Infestation TI	Infestation PBI	Weighted (RI) reduced model
				- - *Percent* - -		
1	1	0.23	0.40	12.1	—	0.12
	2	0.07	0.13	43.5	—	0.13
	3	0.00	0.08	65.6	—	0.12
2	1	0.22	0.16	69.2	45.8	0.27
	2	0.16	0.09	52.2	43.1	0.11
	3	0.12	0.05	49.2	28.1	0.07
3	1	0.19	0.09	72.4	63.3	0.17

generation had 1.72 annual growth flushes compared to 4.33 in uninfested trees. Infested trees in the first generation also were significantly smaller (30.2 cm) at the end of the year compared to unattacked trees (71.0 cm) or trees attacked only in the second (50.7 cm) or third (55.6 cm) generations.

The results of the analysis presented in table 4 suggest that control of the first generation during the first year should be a high priority. However, infestation levels during this generation tend to be low because the tip moth population is in the process of becoming established in the plantation. Consequently, control of tip moth in the first generation will affect only a small proportion of trees in the stand. Therefore, since tip moth attack is not uniform within or between years, an analysis of the relative impact weighted by expected or observed infestation level is appropriate (table 4). The greatest weighted impact occurred in the first generation of the second and third growing seasons. Accordingly, if these infestation levels are representative of the temporal attack pattern which occurs in the first three growing seasons, and if the cost of control is approximately the same for each generation, then control of the first generation in the second and third growing seasons should be given the highest priority.

Impact of Pine Tip Moth Attack on Loblolly Pine Volume

Impact of pine tip moth attack on pine volume is obtained by adjusting the average height of the dominant and codominant trees. The first step is to use the linked height models to obtain predicted pine heights given a specified level of tip moth attack. These heights are used to obtain the reduction in height due to tip moth attack. This is done by taking the difference between the predicted height without tip moth attack (0 infestation) and the predicted height given the specified levels of tip moth attack. The height of the dominant and codominant pines is then adjusted based upon the calculated reduction in height. The pine volume is then calculated from the yield equations. This procedure assumes that the growth impact due to tip moth attack at age 3 will continue until age 15. This assumption has been shown to hold true for loblolly pine attacked by the pine tip moth in the southern U.S. (Hedden 1998).

The potential maximum reduction in height at age 3 using the reduced model based upon 100 percent infested terminals is 4 feet. Therefore, for this model, impact due to tip moth attack could range from 0 to 4 feet. Table 5 shows the reduction in total pine cubic foot volume (inside bark) per acre at age 15 for pine densities of 400, 500, 600 and 700 trees per acre at age 5 with a site index (base age 25) of 70 feet. This table can be used to obtain an estimate of the volume impact due to tip moth infestation for any calculated reduction in height. In this study, the reduction in tree height using the observed average percent infested terminals (table 4) was 1.63 feet. This height reduction corresponds to a reduction in total volume (inside bark) of between 180 and 204 cubic feet per acre at age 15 depending on the pine density. This represents an approximate reduction in pine volume per acre at age 15 of about 8 percent.

Table 5—Reduction in total pine cubic foot volume (inside bark) per acre at age 15 for pine densities of 400, 500, 600 and 700 trees per acre at age 5 with a site index (base age 25) of 70 feet

Reduction in height (ft)	Trees per acre 400	500	600	700
0.0	0	0	0	0
0.5	101	110	122	130
1.0	197	215	239	253
1.5	289	316	349	371
2.0	376	412	454	483
2.5	458	504	552	589
3.0	536	591	645	689
3.5	609	674	731	784
4.0	677	752	812	872

This procedure can be used to calculate volume loss due to tip moth attack for any combination of planting density, age, or site index using the appropriate yield equations (Burkhart and others 1972). Furthermore, this method of modifying the average height of dominant and codominant trees can be used to estimate losses due to tip moth attack using other loblolly pine growth and yield models (Amateis and others 1984, Bailey and others 1985, Hafley and others 1982).

Economic Evaluation of Tip Moth Control

Decisions to control Nantucket pine tip moth should be made by comparing the costs and benefits of control. The benefits are the increases in wood yield at harvest due to a reduction in tip moth damage. The costs are the financial resources needed to reduce tip moth attack. An example of an economic analysis of pine tip moth control showing both the pertinent costs and benefits is described below. This example will assess the economic feasibility of using loblolly pine seedlings treated with an insecticide in the nursery to reduce tip moth damage in the first tip moth generation after planting.

Table 6 shows the estimated impact of pine tip moth infestation on loblolly pine yield from moths attacking trees during the first generation of the first growing season. Tip moth attack causes a linear decline in pine pulpwood yield. Also shown are the present values of the reduction in pine yield for discount rates of 4 percent, 6 percent and 8 percent due to moth attack. The insecticide treatment cost for pine seedlings in the nursery is about $0.003 per seedling (Doggett 1998) which amounts to $2.62 per acre if 875 trees per acre are planted. The economic threshold (where the costs equal the benefits) for Nantucket pine tip moth control in the first generation of the first season are terminal infestation levels of 3.9, 6.9 and 9.2 percent, respectively, for the present values of 4, 6 and 8 percent. Since the observed average terminal infestation level in the untreated plots for the first generation in the first season was 12.1 percent, nursery treatment in this example would have been cost effective for the 4, 6 and 8 discount rates assuming that complete control resulted from nursery treatment of the seedlings. Cost effectiveness of controlling other tip moth generations can be evaluated in a similar manner.

The type of analysis presented here allows the identification of the infestation level associated with an economic threshold in each tip moth generation. This information, when used with methods for predicting expected tip moth levels, will assist in the development of an economically viable program for control of the Nantucket pine tip moth in areas similar to the coastal plain of North Carolina.

CONCLUSION

The Nantucket pine tip moth has the potential to cause significant growth loss in planted stands of loblolly pine in

Table 6—Impact on NPV for attack in the 1st generation after planting in a 15-year-old pine stand SI 70 planted at 875 trees per acre

Terminal infestation	Height loss	DBH loss	Pulpwood loss	Present value loss (%)		
				4	6	8
Percent	*Ft*	*In.*	*Cords*	------ *Dollars* -------		
0	0.00	0.00	0.0	0.00	0.00	0.00
5	0.08	0.03	0.2	3.33	2.50	1.89
10	0.16	0.07	0.3	5.00	3.75	2.83
15	0.24	0.10	0.5	8.34	6.26	4.73
20	0.32	0.13	0.7	11.66	8.76	6.62
25	0.40	0.16	0.9	14.99	11.27	8.51
30	0.48	0.20	1.1	18.32	13.77	10.40
35	0.56	0.23	1.2	19.99	15.02	11.35
40	0.64	0.26	1.4	23.32	17.52	13.24
45	0.72	0.29	1.6	26.65	20.03	15.13
50	0.80	0.33	1.7	28.32	21.28	16.08
55	0.88	0.36	1.9	31.65	23.78	17.97
60	0.96	0.39	2.1	34.98	26.29	19.86
65	1.03	0.42	2.2	36.65	27.54	20.80
70	1.11	0.45	2.4	39.98	30.04	22.70
75	1.19	0.49	2.6	43.31	32.55	24.59
80	1.27	0.52	2.7	44.98	33.80	25.53
85	1.35	0.55	2.9	48.31	36.30	27.43
90	1.43	0.58	3.0	49.97	37.55	28.37
95	1.51	0.62	3.2	53.30	40.06	30.26
100	1.59	0.65	3.3	54.97	41.31	31.21

the southern United States. The models relating tree height to tip moth infestation level developed in this study show that tip moth attack during the first generation of the year is especially harmful, and that this generation is relatively easy to control. These models also can be used to calibrate pine growth and yield models to estimate the impact of this pest on pine volume. Furthermore, the output on pine volume loss due to tip moth attack can be used to economically evaluate potential tip moth control programs.

ACKNOWLEDGMENTS

Data in this study were collected as part of a cooperative project between Clemson University and Weyerhaeuser Company to study pine resistance to tip moth attack. The author thanks Weyerhaeuser for the their support.

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INTERACTION OF FOREST MANAGEMENT PRACTICES AND TIP MOTH DAMAGE

John T. Nowak[1]

Abstract—Intensive forest management practices have been shown to increase tree growth and shorten rotation time. However, they may also increase the need for insect pest management because of higher infestation levels and lower action thresholds. The Nantucket pine tip moth (*Rhyacionia frustrana* [Comstock]) is one insect that is expected to become more important with more intensive forest management practices. Two studies were developed to investigate these relationships. Treatments included various combinations of herbicide applications, irrigation, fertilization, and insecticide applications. These studies demonstrated that tip moth management improves tree growth. Tip moth damage increased due to weed control, but not due to N fertilization. Nitrogen fertilization did increase the number of tip moth pupae per shoot, however. In conclusion tip moth populations can increase due to intensive management practices, and insect control should be considered a part of efforts to maximize tree growth.

INTRODUCTION

The demand for forest products in the United States is growing while the land base for producing these commodities is shrinking as a result of conversions to other uses, increased land fragmentation, and concerns about endangered species and old growth forests. In order to meet timber and fiber needs, commercial forests must be managed more efficiently. Intensive management practices, such as herbaceous weed control, irrigation, and fertilization can increase tree growth and shorten rotation time (Pritchett and Smith 1972, Haywood 1986, Zutter and others 1986, Creighton and others 1987). Unfortunately, they may also increase the frequency and severity of pest infestations (Hedden and Nebeker 1984, Ross and others 1990). There is a critical need for studies on the effects of intensive forest management practices on pest insect populations.

Loblolly pine (*Pinus taeda* L.) is the most commercially important tree species in the southeastern United States. Several insects are associated with young stands of loblolly pine and are likely to become more important as management intensity increases. The Nantucket pine tip moth (*Rhyacionia frustrana* [Comstock]), is one such species (Sun and others 1998). Feeding by tip moth larvae can decrease tree growth in the early years following stand establishment (Warren 1964, Beal 1967, Lashomb and others 1978, Berisford and others 1989). Tip moth infestation levels often vary with intensity of silvicultural manipulations, such as mechanical site preparation, herbaceous weed control, and fertilization (Hertel and Benjamin 1977, White and others 1984, Ross and Berisford 1990, Ross and others 1990). Miller and Stephen (1983) concluded that differences in vegetation levels were not a good indicator of tip moth damage. However, Ross and others (1990) found that herbicide-treated plots had signicantly more tip moth damage than control plots during the first two growing seasons of a study conducted on the upper Coastal Plain of Georgia. Pritchett and Smith (1972) showed significant reductions in tip moth damage levels related to phosphorus (P) and potassium (K) fertilization, but no differences were observed after nitrogen (N) fertilization.

In January 1995, International Paper Corporation established a study of loblolly pine at their Southlands Experimental Research Forest near Bainbridge, GA to determine the maximum growth potential of loblolly pine using several hierarchies of cultural treatments. We examined the pest problems associated with these intensively managed loblolly pine within the first five years following stand establishment. Our objectives were to monitor insect pest establishment and to quantify insect associated growth losses among the different silvicultural treatments. A second study was established in 1999, near Powelton, GA to further examine the effects of fertilization and herbicide application on tip moth development and infestation levels.

MATERIALS AND METHODS

Bainbridge Study

This study was conducted in Decatur County, GA, about 20 km south of Bainbridge. The soil type was classified as a Wagram-troup complex and the site index was estimated to be 59 (base age 25; loblolly pine) (Personal communication. Tom Cooksey, Southlands Experiment Forest, International Paper Corp., Bainbridge, GA, 31717). The main study area was established on an old agricultural field that had been used to grow soybeans and watermelon. The surrounding plant community included a mixture of agricultural crop lands, hardwood forests, and longleaf (*Pinus palustris* Mill.) and loblolly pine forests of varying age classes.

A randomized complete block design with three blocks of four treatments was established. Each treatment plot was 0.2 ha, and contained 216 1-0 seedlings (grown for one year in the nursery before being planted in the field) (12 rows of 18 seedlings) hand planted in January 1995. One row on the end of each plot was designated as a border row and

[1] Graduate Research Assistant, 413 BioScience Building, University of Georgia, Athens, GA 30602.

Citation for proceedings: Berisford, C. Wayne; Grosman, Donald M., eds. 2002. The Nantucket pine tip moth: old problems, new research. Proceedings of an informal conference, the Entomological Society of America, annual meeting. 1999 December 12–16. Gen. Tech. Rep. SRS–51. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 68 p.

excluded from subsequent evaluations of insect infestation. Four improved loblolly pine seed sources from a nursery in North Carolina were blocked randomly within each plot. The site was subsoiled on 4 m centers and harrowed two months prior to planting. Sulfometuron (Oust®) (0.28 kg [AI]/ha) herbicide was applied once prior to planting and glyphosphate (Accord® 1.8 kg [AI]/ha) was applied twice prior to planting and then monthly during the growing season throughout the study to minimize herbaceous weeds.

The treatments were herbaceous weed control (H), H + irrigation (I), H + I + fertilization (F), and H + I + F + pest control (P). In the original study design, the control treatment was the H treatment. However, because weed control has been shown to influence tip moth damage levels (Ross and others 1990), we included three additional control plots in a nearby stand that represented more typical forest management. The control stand (C), approximately 250 ha in size, was located <1 km north of the main study site and contained 1-0 seedlings machine planted concurrently with the main study site. Except for a site preparation application of herbicides (Sulfometuron) and a prescribed burn prior to planting, competing vegetation was not managed in this stand. A number of factors besides weed control could contribute to differences between the control plots and the more intensively managed main study plots. However, we believe that these comparisons provide useful information regarding the potential differences between intensive cultural practices and traditional forest management.

A dripline irrigation and fertigation (water and nutrients) system (Netafim Irrigation, Altamonte Springs, FL) was used to add water and nutrients. Water was pumped directly from a nearby lake onto the treatments receiving irrigation on a nightly interval at a rate of 18 cm per year. Nitrogen was applied to the treatments receiving fertilizer at rates of 45 kg/ha in 1995, 79 kg/ha in 1996, 133 kg/ha in 1997 and 111 kg/ha in 1998 using an 8-2-8 liquid fertilizer formulation. Fertilizer applications were distributed evenly from April through November. Permethrin (Pounce® 3.2 EC, FMC Corporation, Philadelphia, PA) (1.1 kg [AI]/2.5 ha) and acephate (Orthene® 75 Turf, Tree and Ornamental, Valent USA Corp.) (2.2 kg [AI]/78 liters) were applied separately with backpack sprayers (Solo®, Newport News, VA) to the H+I+F+P treatment throughout each growing season at biweekly intervals in 1995–1997. Insecticide applications were discontinued for the first seven months of 1998, but were resumed in September. The insecticide treatments had been discontinued because of the large size of the trees and the lack of tip moth in the previous two years.

Nantucket pine tip moth damage was evaluated three times annually following the first, second, and combined third and fourth generations. The third and fourth generations were combined into one evaluation date because of considerable damage overlap between these two generations (Berisford and others 1992). Evaluation dates were timed to coincide with either the tip moth pupal stage or just after adult emergence (Ross and Berisford 1990). Forty trees per treatment per block were randomly selected on each evaluation date. All shoots were examined for tip moth damage during each evaluation in 1995–1997. However, due to the size of the trees in 1998, only the terminal and top 2 branch whorls were examined. There is a significant correlation between terminal and top whorl damage and whole tree damage (Fettig and Berisford 1999). Damage was recorded as the percentage of damaged shoots; a shoot was defined as an apical meristem containing at least 5 cm of foliage.

Basal diameter and total height were measured following each growing season. For comparative purposes, a tree stem volume index was calculated by multiplying the square of the basal diameter times height (D^2H). This volume index has been shown to correlate well with above-ground biomass (Hatchell and others 1985).

The control treatment means for insect damage were qualitatively compared to the combined means of the main study area because the control area was separate from the main study design. The growth data for the control site are included to illustrate the potential growth gains from intensive forestry. However, because factors other than weed control (i.e. site preparation and genetic source) could also have influenced insect damage levels and growth differences, statistical comparisons are not made between the main study site and the control site representing typical forest management. The data are included only to provide comparisons between typical forest management and intensive cultural practices for potential growth gains and implications for insect population dynamics.

Powelton Study

This study was conducted in Hancock County, GA near Powelton in 1999. A randomized complete block design was established in a two-year-old loblolly pine plantation. Each treatment plot was about 0.05 ha and had been machine planted with about 100 1-0 seedlings. The treatments were control, N fertilization (N-Fert), herbicide (Herb), and herbicide and N fertilizer (Herb-N).

The herbicide and fertilizer treatments were applied on 5 May and 21 July. The N fertilizer was applied at a rate of 107 kg/ha of elemental N in the form of 46 percent elemental urea. Glyphosphate (Accord® 1.8 kg [AI]/ha) was applied with backpack sprayers (Solo®, Newport News, VA). Treatment trees were covered with plastic bags for <15 min during herbicide application because glyphosphate is activite on pine trees.

Twenty-five trees per treatment per block were randomly selected on each evaluation date. Tip moth damage was evaluated on a whole tree basis three times annually following each of the three generations in a manner consistent with the Bainbridge study. Fifty tip moth infested shoots per treatment per block were collected near the end of the third generation and returned to the laboratory for examination. For each shoot, length of tip moth damage, number of insects, and life stages present were recorded.

Statistical Analysis

Tip moth infestation percentages were arcsine square root transformed and subjected to an analysis of variance (ANOVA) by each evaluation date. The insect damage data

are reported as the non-transformed means. Tree growth data were compared by ANOVA for each evaluation date. Insect damage and growth treatment data were analyzed as a randomized complete block design and means were separated using Proc GLM and Tukey's Studentized Range Test (SAS Institute 1988).

RESULTS

Bainbridge Study

Tip moth damage levels exceeded 10 percent only twice during this study, in 1995 and 1998 (fig. 1). Tip moth damage reached moderate levels in the third and fourth generation of 1995 and then dropped below 3 percent in 1996 and 1997 in the main study area. At the end of 1998, tip moth damage was ca. 80 percent in the main study area. Damage in the control treatment never exceeded 30 percent, even when damage was relatively high in the main study area.

No significant differences were detected in tip moth damage among the H, H+I, and H+I+F treatments in any year ($P > 0.05$; Tukey test) and these treatments are combined for analysis (fig. 1). Percent damage was significantly higher for these treatments than the H+I+F+P treatment during the highest infestation periods (generations 3 & 4 in October 1995 ($F = 25.46$; d.f. = 3,6; $P = 0.0008$) and October 1998 ($F = 13.55$; d.f. = 3,6; $P = 0.0044$)) (fig. 1). However, at lower damage levels, no significant differences were found. Tip moth damage levels were noticeably higher in the main study area than in the control area during the periods of highest infestation (fig. 1). There were no significant differences in tip moth damage levels among the four different seed sources used in the main study area ($P > 0.05$).

Significant differences were observed in height and volume among all treatments during 1995 and 1996 (figs. 2 and 3). The H+I+F+P treatment had significantly greater height and volume measurements than the other treatments at the end of 1995, 1996, and 1998. In 1997, there was no significant difference in height between the H+I+F treatment and the H+I+F+P treatment (fig. 2), but the H+I+F+P treatment had a significantly greater volume index (fig. 3). There was no significant difference in height between the H+I and H+I+F treatments in 1998, but the H+I+F treatment had a significantly higher volume index (fig. 3). The control treatment had the lowest values for height and volume measurements throughout the study (figs. 2 and 3).

Powelton Study

Tip moth damage ranged between 16 and 39 percent (fig. 4). There were no treatment differences in the second tip moth generation. However, significant differences were detected with ANOVA within treatment for percent tip moth infestation ($F = 5.03$; d.f. = 3,6; $P = 0.0446$), number of pupae per shoot ($F = 13.66$; d.f. = 3,6; $P = 0.0043$), and tree diameter ($F =$

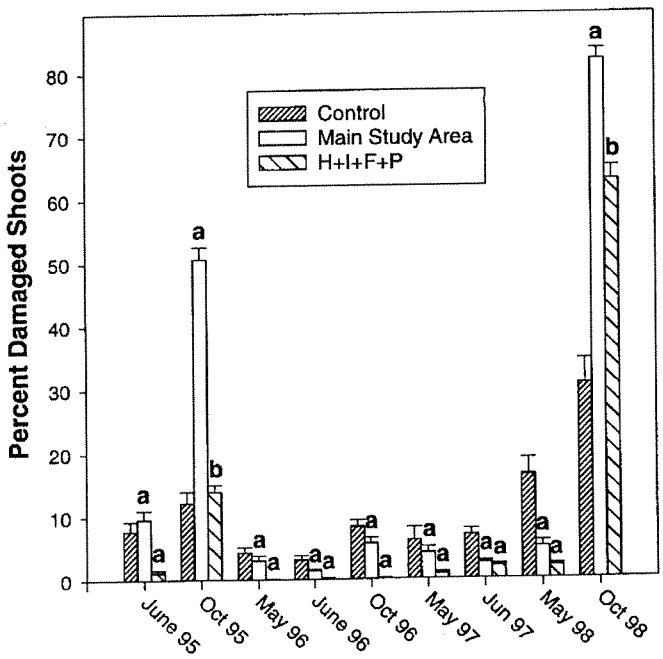

Figure 1—Mean percent (+/-SE) of loblolly pine shoots damaged by Nantucket pine tip moth during 1995–1998 in Bainbridge, GA. Three treatments means [herbicide (H), H + irrigation (I), and H + I + fertilizer (F)] are classified as the Main Study Area for simplicity and the lack statistical differences ($P > 0.05$;Tukey test). Bars with the same letter for each sample date are not significantly different (n = 480; $P > 0.05$; Tukey test). Control means (n = 120) are provided for comparative purposes only and are not included in the statistical analysis.

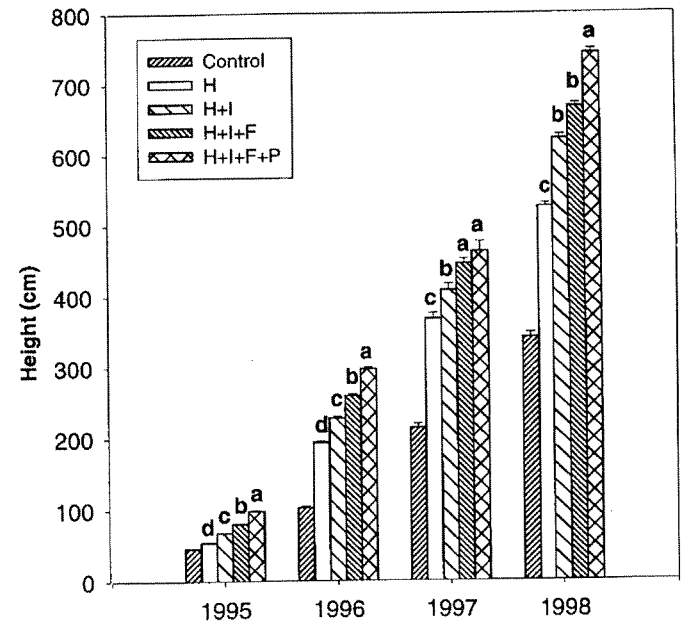

Figure 2—Mean tree height (+/-SE) for four growing seasons in a study conducted in Bainbridge, GA, following yearly cultural treatments: Herbicide (H), H + irrigation (I), H + I + fertilizer (F), and H + I + F + pest control (P). Bars with the same letter are not significantly different (n = 480; $P > 0.05$; Tukey test). Control means (n = 120) are provided for comparative purposes only and are not included in the statistical analysis.

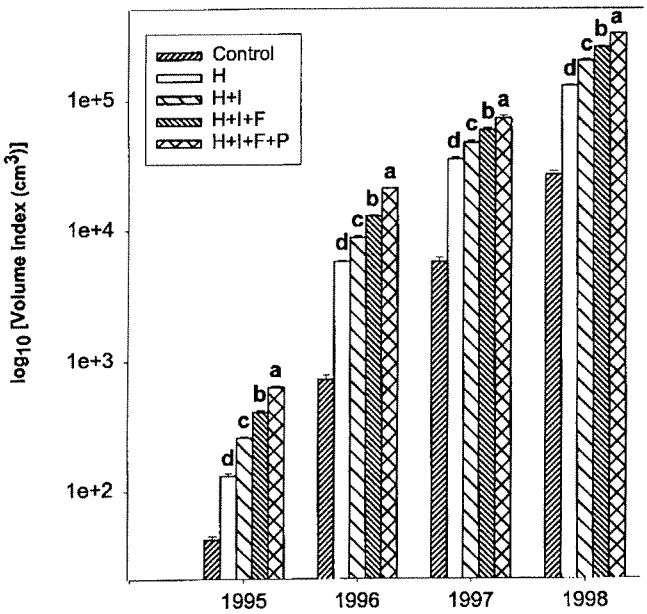

Figure 3—Mean tree volume index (+/-SE) (basal diameter-squared times height) for four growing seasons in a study in Bainbridge, GA following yearly cultural treatments: Herbicide (H), H + irrigation (I), H + I + fertilizer (F), and H + I + F + pest control (P). Bars with the same letter are not significantly different (n = 480; $P > 0.05$; Tukey test). Control means (n = 120) are provided for comparative purposes only and are not included in the statistical analysis.

10.42; d.f. = 3,6; $P = 0.0086$) at the end of the third generation. Tip moth damage was significantly higher in the Herb-N and Herb treatments than in the control treatment (fig. 4). Mean number of tip moth per shoot ranged between 0.33 and 0.78 (fig. 5). There were significantly more pupae in the Herb-N treatment than in any of the other treatments, but none of the other treatments varied statistically (fig. 5). Mean tree diameter was significantly greater in the Herb and Herb-N treatments than in the N-fert and control treatments, which did not differ significantly (fig. 6). However, there was no treatment difference in tree height ($F = 1.97$; d.f. = 3,6; $P = 0.2205$).

DISCUSSION

Tip moth damage in the Bainbridge study was at the highest level after the trees had exceeded what is normally considered susceptible size (Berisford 1988). Because of the absence of significant tip moth infestation after the 1995 growing season, it was thought that the trees in the more intensive treatments may have simply outgrown their susceptibility to attack in the first growing season. However, the high tip moth damage in 1998 dispelled this hypothesis. It was thought that perhaps the pitch pine tip moth (*R. rigidana* [Fernald]) was causing the infestation in 1998 because *R. rigidana* are more common in taller trees than *R. frustrana* (Berisford 1988). However, the moths were identified as *R. frustrana* based on Yates' (1967) key.

In the Bainbridge study, tip moth infestation levels fluctuated more in the main study area without competing vegetation than in the control area with competing vegetation. Similar fluctuations were found by Miller and Stephen (1983), where

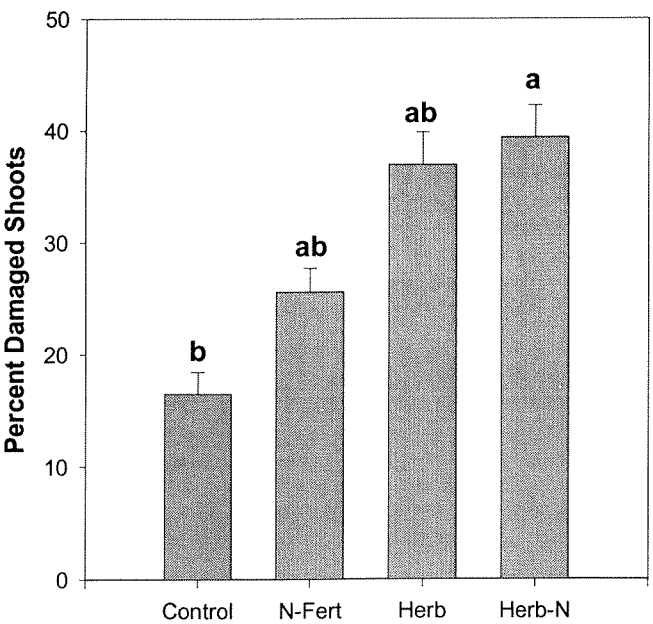

Figure 4—Mean percent (+/-SE) of loblolly pine shoots damaged by Nantucket pine tip moth during the third tip moth generation of 1999 in a study in Powelton, GA following cultural treatments: control, N fertilization (N-fert), herbicide (Herb), and herbicide application and N fertilization (Herb-N). Bars with the same letter for each sample date are not significantly different (n = 240; $P > 0.05$; Tukey test).

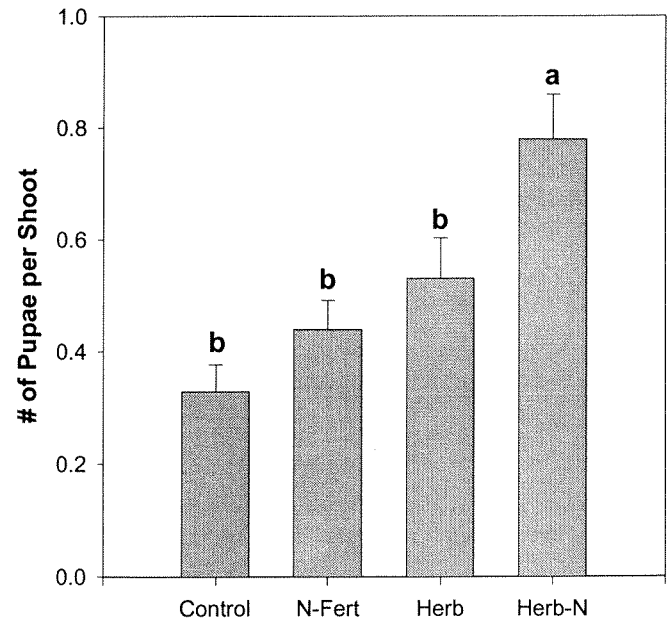

Figure 5—Mean number of tip moth pupae per shoot (+/-SE) for the third tip moth generation in a study conducted in Powelton, GA, following cultural treatments: control, N fertilization (N-fert), herbicide (Herb), and herbicide application and N fertilization (Herb-N). Bars with the same letter are not significantly different (n = 300; $P > 0.05$; Tukey test).

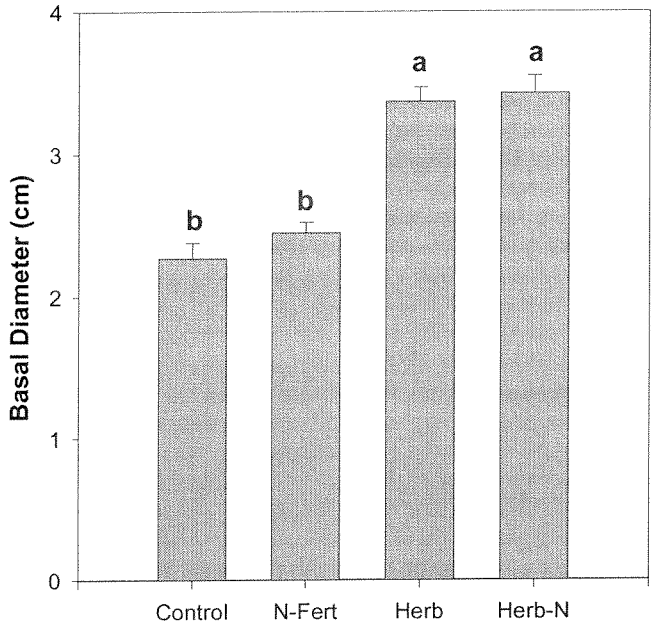

Figure 6—Mean tree diameter (+/-SE) for the third tip moth generation in a study conducted in Powelton, GA, following cultural treatments: control, N fertilization (N-fert), herbicide (Herb), and herbicide application and N fertilization (Herb-N). Bars with the same letter are not significantly different (n = 240; $P > 0.05$; Tukey test).

tip moth damage levels fluctuated more in areas with low competing vegetation than in areas with high vegetation levels. Tip moth population levels in areas with competing vegetation appear to be more stable than populations in areas without competing vegetation. One possible reason for this could be that the tip moth natural enemy complex exerts a more consistent influence in areas with herbaceous weeds, perhaps because of a more favorable microclimate and the presence of food sources such as pollen and nectar (Pimentel 1961, Strong 1984). In a previous study, total parasitism was higher in areas with competing vegetation than in adjacent areas with significantly less vegetation (McCravy and Berisford *In press*). However, parasitism data were not collected in this study.

Irrigation and fertilization significantly increased tree growth, but did not affect tip moth infestation levels. In a greenhouse study, Ross and Berisford (1990) concluded that management practices that increase water and nutrient availability to loblolly pine increase the amount of tip moth infestation. Results of the fertilization treatments are consistent with other studies concerning the effects of fertilization on tip moth infestation levels (Pritchett and Smith 1972, Berisford and others 1989). However, none of these studies, including this one, accounted for the number of tip moth larvae or pupae per individual shoot. Ross and Berisford (1990) found that pupal densities were significantly higher in potted seedlings with high nutrient levels. More intensive studies are needed to investigate the effects of fertilization on the amount of tip moth attacks and subsequent infestation. If N fertilization increases tip moth infestation, it might not be economically feasible to apply fertilizer if growth gains were lost to insect infestation. On the other hand, it is possible that fertilization could be used to increase tree vigor and thereby reduce the impact of tip moth infestation.

The Powelton study was designed to further evaluate the effects of fertilization and weed control on tip moth damage levels and development. It has been shown that a reduction in competing vegetation can lead to an increase in tip moth damage levels (Miller and Stephen 1983, Ross and others 1990). However, the Bainbridge study did not adequately address this issue because a true control was not included in the original study design. In the Powelton study, herbicide applications reduced competing vegetation and subsequently increased tip moth damage. Herbicide applications coupled with N fertilization also increased the number of pupae per shoot. This indicates that intensive forest management practices such as herbaceous weed control can increase tip moth populations and subsequent damage.

In the Powelton study, we found that fertilization alone did not increase tip moth damage or the number of pupae present per shoot. However, there were also no differences in tree height or diameter due to N fertilization. The Powelton study has only lasted one year and tip moth damage estimates were only recorded in one generation after the plots were treated. It is possible that the trees and also the insects have not had time to respond the N fertilization. The Powelton study will continue for three more generations and foliar analysis will be performed. It is too early in the experiment to conclude that N fertilizer will not have an effect on tip moth damage levels or on insect development in contrast to Ross and Berisford (1990).

Insecticide applications increased tree growth 27 percent over the H+I+F treatment even though tip moth infestations in the Bainbridge study were low compared to many other studies (Lashomb and others 1978, Miller and Stephen 1983, Ross and others 1990). In 1998, the insecticide applications were discontinued because of low insect infestation in the previous two years. The applications were resumed once heavy damage began to reappear in September of 1998. Therefore, tip moth infestation in the pest control plots was significantly lower than the other treatments, but could have been even lower if insecticide applications had been made in a manner consistent with previous years. It has been argued that growth losses due to tip moth infestation are transitory (Williston and Barras 1977); however, this was not evident in our four year study. Future growth measurements are intended. Longer-term studies have shown that growth increases due to tip moth management are maintained (Cade and Hedden 1987, Unpublished data. Wayne Berisford, Department of Entomology, University of Georgia, Athens, GA, 30602).

In conclusion, intensive forest management practices such as herbaceous weed control and N fertilization can in some cases exacerbate tip moth problems and may disrupt tip moth population dynamics. However, tip moth control can reduce grow losses associated with feeding damage.

ACKNOWLEDGMENTS

The author thanks Tom Cooksey (International Paper Corporation) for his assistance throughout this study. The author also thanks the following people for help in data collection and technical help: Chris Asaro, Anthony Coody, Charles Gasset, Richard Garland, Mitch Gibbs, Nick LeCroy, and Joe Petty (University of Georgia). The author is also grateful to International Paper Corporation and the Timber Company for providing access to research sites. This research was supported in part by funds from the USDA Forest Service, Southern Research Station, and the University of Georgia Pine Tip Moth Research Consortium.

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EVALUATION OF CANDIDATE INSECTICIDES FOR CONTROL OF THE NANTUCKET PINE TIP MOTH (LEPIDOPTERA:TORTRICIDAE)

Mark J. Dalusky and C. Wayne Berisford[1]

ABSTRACT—Initial screening in 1995 compared the efficacy of Capture®, Dimlin®, Foray®, Mimic®, Neem®, Pounce®, and Tempo® in controlling infestation by the Nantucket pine tip moth, *Rhyacionia frustrana* (Comstock). Orthene®TTO, Tame® and a tank-mix of the two were added to the trials in 1996. All compounds tested were significantly better than the check regarding infestation of terminal and top whorl shoots by Nantucket pine tip moth. All sprays were timed for a contact-type insecticide, unless otherwise stated, following the methods of Berisford and others (1984), using degree-day accumulation triggered by male moth flight. In the Piedmont, the pyrethroids Tempo®, Capture® and Pounce® and the insect growth regulator (IGR) Mimic® performed best with Dimlin®, Neem® and Foray® being somewhat less effective. Test results from the Alabama Coastal Plain were similar with Foray® joining the top group. In 1996, Neem® and Dimlin® were dropped in favor of Orthene® and Tame® alone and in combination. All treatments in the Coastal Plain and Piedmont tests were significantly better than control plots. Only two sprays (1 of Foray® and 1 of Orthene® applied on a contact timing) failed to limit infestation in the top whorl below 10 percent. On an epidemic Virginia site, all treatments were significantly better than controls with the pyrethroids, Orthene®/Tame mixtures and Foray® plus a UV screen grouping together followed by the various tank-mixes and Foray® minus the UV screen. In 1997, Warrior®, a pyrethroid, was tested against third and fourth generation tip moth in the upper Coastal Plain of Georgia. Top whorl infestation was held below 5 percent for both generations compared to a mean of 30 percent for Pounce®. In 1998, Imidan, an organophosphate, was tested at 2 rates for control of second generation Nantucket pine tip moth on a Piedmont site near Athens, GA. Control was excellent being at or near zero percent infestation in treatment plots.

INTRODUCTION

Historically, chemical control of the Nantucket pine tip moth (NPTM) has been accomplished by calendar sprays every 2 weeks beginning in spring and continuing through fall. Timing of insecticide applications based on degree-day driven models (Garguillo and others 1985, Fettig and others 1999) has both improved effectiveness and dramatically reduced the number of sprays required to achieve satisfactory control. Initial efficacy testing was conducted with dimethoate, acephate (both organophosphates) and then with fenvalerate, a synthetic pyrethroid (Berisford and others 1984, Garguillo and others 1985). Clarke and others (1990) and DeBarr (1982) suggested that repeated spraying with fenvalerate and azinphosmethyl in a seed orchard setting induced secondary scale outbreaks that reached epidemic proportions in some cases. Some broad-spectrum insecticides are toxic to tip moth natural enemies (McCravy and others 2001) and may worsen tip moth infestations when poorly timed. Recent regulatory actions taken by the U.S. Environmental Protection Agency, most notably the review of carbamate, chlorinated hydrocarbon and organophosphate based insecticides under the Food Quality Protection Act, has reduced the number of compounds available and threatened the continued existence of several forestry-use labels, due to their minor-use designation. With this last trend in mind, we undertook to screen some new and old compounds for efficacy in controlling tip moth infestation in loblolly pine plantations.

METHODS

We began initial screening of potential tip moth control chemicals in 1995 which compared the efficacy of Capture® (FMC Corp.), Dimilin® (Uniroyal), Foray® (Abbott Labs), Mimic® (Rohm and Haas Co.), Neem® (Phero Tech Inc.), Pounce® (FMC Corp.) and Tempo® (Bayer Corp.) in controlling infestation by NPTM (table 1). Neem® and Dimlin® were dropped in favor of Orthene TTO®, Tame® and a combination of the two (Valent USA) in 1996. The 1995 and 1996 trials were conducted in the Coastal Plain of Alabama in Escambia and Monroe Counties and in the Piedmont Plateau in Oglethorpe County near Lexington, GA. A group trial was also conducted in an epidemic population of tip moth in loblolly pine in southern Virginia in Southhampton County near Emporia, VA. during the fall of 1996. In 1997, Warrior® (Zeneca Ag Products), a pyrethroid, was tested against third and fourth generation tip moth in the upper Coastal Plain in Burke County near Waynesboro, GA. In 1998, Imidan® (Gowan Co.), an organophosphate, was tested at two rates for second generation tip moth control on a Piedmont site near Athens, GA.

All sprays were timed for a contact-type insecticide, unless stated otherwise, following the method of Garguillo and others (1985) revised by Fettig and others (1999), using degree-day accumulation triggered by male moth flight. The basic experimental design was similar for all tests regardless of location or year. Trials consisted of randomized complete blocks with 4–6 replicates of 8–10 tree plots. All compounds were applied in water with Solo ® hand-pump sprayers.

[1] Dalusky, Research Coordinator, Department of Entomology, University of Georgia, Athens, Georgia 30602; and Berisford, Professor of Entomology

Citation for proceedings: Berisford, C. Wayne; Grosman, Donald M., eds. 2002. The Nantucket pine tip moth: old problems, new research. Proceedings of an informal conference, the Entomological Society of America, annual meeting. 1999 December 12–16. Gen. Tech. Rep. SRS–51. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 68 p.

Table 1—Products tested for control of Nantucket pine tip moth:1995–1998

Product (formulation)	Class	Percent A.I. applied	Label rate	Active ingredients	Label status[a]
Capture (2EC)	Pyrethroid	0.025	8–12 oz/ac	Bifenthrin	None
Pounce (3.2EC)	Pyrethroid	0.024	4–8 oz/ac	Permethrin	Full
Tame (2.4EC)	Pyrethroid	0.025	8–16 oz/ac	Fenpropathrin	Partial
Tempo (2S)	Pyrethroid	0.008	6–8 oz/ac	Cyfluthrin	Partial
Warrior (1EC)	Pyrethroid	0.016 0.032	3.2–5.12 oz/ac	Lambda-cyhalothrin	24C
Imidan (70WP)	Organo-phosphate	2.0 4.0	1.33 lb/Ac	Phosmet	Partial
Orthene TTO (78%WP)	Organo-phosphate	1.1	0.05–1 lb/ac	Acephate	Partial
Foray (48B)	Bacterial	NA	0.125–1 gal per acre	*Bacillus thuringiensis*	Full
Mimic (2F)	Insect growth regulator	0.014	8.0 oz/ac (0.12lb.)	Tebufenozide	Full

[a] full= full EPA label for both pest, crop, and application technique; partial = either pest, crop, or application labeled but not all three; and 24C = special local need state label.

Water was pH adjusted to 5.5 for Orthene® and Imidan® applications on recommendations by technical representatives of the manufacturers . Pines were sprayed with a fine mist until the foliage was visibly wet but not until run-off. Mixing rates were extrapolated from existing labels or were supplied by technical reps (see table 1 for list). Frequently, in large group tests, all compounds were applied on the same date which may not have been the optimum date for a particular chemical. This was necessary due to the logistics of traveling to sites with sufficient NPTM infestation to make testing worthwhile. When NPTM damage was readily visible, the number of infested shoots in the top whorl (Fettig and Berisford 1999) were recorded for all treatments and untreated controls. Typically, the percent infestation in the terminal and top whorl shoots was analyzed via ANOVA at alpha=0.05. Means were separated with a Tukey test for all pairwise multiple comparisons or the non-parametric ANOVA on ranks with means separated by Student-Newman-Keuls method when assumptions of normality and equal variances were not met (SigmaStat Version 2.03, SPSS Inc. 1997).

Experiment 1: Spring/Summer 1995

Initial screening compared the efficacy of Capture® 2EC, Dimlin®, Foray® 48B, Mimic® 2F, Neem®, Pounce® 3.2EC and Tempo® 2S for control of second generation NPTM infestation. Testing was conducted during late spring and early summer in the Alabama Coastal Plain and in the Piedmont region of Georgia. Neem® and Dimlin® were dropped from subsequent testing in favor of Orthene® and Tame®.

Experiment 2: Spring/Summer 1996

Group testing was performed during the first generation of moths in the Alabama Coastal Plain and in the upper Coastal Plain of Georgia. An additional test was conducted for third generation control in southern Virginia on an upper Coastal Plain site experiencing an epidemic tip moth infestation. Orthene® TTO (78 percent WP), an organophosphate, and Tame® 2.4EC, a pyrethroid, alone and in combination were added to the tests this year. On the Georgia and Virginia sites, a two-spray regime of these products was also evaluated. The second application occurred ca. 8 days after the initial spray. Combination sprays of Orthene® and Tame® were dropped from testing in 1997.

Experiment 3: Spring/Summer 1997

Group testing was limited to two sprays in the Alabama Coastal Plain during the first tip moth generation. Foray®, Mimic®, Orthene® TTO, Pounce® and Tame® were selected for testing based on demonstrated efficacy and interest in continued testing by the companies involved. The two spray dates (160 and 190 degree-days centigrade) were dictated by adverse weather in the Brewton area, and they occurred

before the optimum predicted pyrethroid spray date (237 degree-days centigrade). This unfortunate circumstance allows us to draw conclusions concerning timing of spray applications only as they relate to the predicted optimum pyrethroid spray date. During the third and fourth generation of moths in the upper Coastal Plain of Georgia, Warrior® 1EC (a pyrethroid new to NPTM control) was evaluated with Pounce® included as a standard for comparison.

Experiment 4: Summer 1998

This test evaluated the efficacy of two rates of Imidan® 70WP (an older organophosphate) for control of second generation moths on a Georgia Piedmont site near Lexington, GA. Pounce® was included as a standard for comparison.

RESULTS AND DISCUSSION

Experiment 1 (1995):

Tip moth populations were moderate at the Coastal Plain site in Alabama with 45 percent of top whorl shoots infested on check trees. In the Georgia Piedmont, the population was somewhat lower with 33 percent of top whorl shoots infested. At this test site, the pyrethroids, Tempo®, Capture® and Pounce® and the insect growth regulator (IGR) Mimic® performed best with Dimlin®, Neem® and Foray® being somewhat less effective (table 2). Test results from the Coastal Plain site were similar with Foray® joining the group of most effective treatments. All treatments were significantly better than controls at both sites ($F=8.36$, $P<0.0001$, $n=5$, $df=7$ for Alabama Coastal Plain site; $F=10.4$, $P<0.0001$, $n=5$, $df=7$ for Georgia Piedmont site).

Experiment 2 (1996):

Tip moth populations in the Alabama Coastal Plain and Georgia upper Coastal Plain sites were low, ranging from 24 percent to 27 percent. All treatments significantly reduced damage compared to checks ($F= 6.33$, $P<0.0001$, $n=5$, $df=8$) at both sites (table 3). Capture®, Pounce®, Tempo®, Orthene®/Tame® mix, Mimic®, Foray® and Orthene® alone (timed for a systemic) performed well. Only 3 sprays (1 of Foray® and 2 of Orthene® applied on a contact timing) failed to contain infestation in the top whorl below 10 percent. We feel that tip moth pressure was not high enough to provide a rigorous test of efficacy on this site. However in Virginia, tip moth populations were at epidemic levels with infestation in the top whorl above 65 percent. Again, all treatments significantly reduced damage level below that of the check plots ($F= 11.3$, $P<0.001$, $n=4$, $df=10$) (table 4). Capture® out-performed both Orthene® applications as well as the initial Orthene®/Tame® mix. All other treatments were not significantly different although there was a trend for Capture® and Tempo® to provide more protection than the remaining treatments. Considering the high tip moth incidence and the asynchronous nature of third generation life stages, all treatments performed well.

Experiment 3 (1997):

In the Alabama Coastal Plain, populations of NPTM were again low ranging from 26 to 33 percent of top whorl shoots on check plots. Spray date 1 occurred on March 3 at 160 degree-days (centigrade), and spray date 2 on March 8 at 190 degree-days. The optimum predicted value from Fettig and others (1999) is 237 degree-days. All treatments were significantly different from untreated control plots regarding

Table 2—Mean percent top-whorl and terminal shoot infestation for group testing in 1995

	Experiment 1: AL Coastal Plain		Experiment 1: GA Piedmont	
Product	Top whorl	Terminal	Top whorl	Terminal
Capture	10.5 a[a]	10.0 a	3.8 a	5.0 a
Tempo	10.8 a	27.5 ab	2.2 a	5.0 a
Pounce	12.9 a	15.0 ab	6.6 ab	20.0 ab
Foray	13.4 a	22.5 ab	19.1 ab	38.6 b
Mimic	17.9 ab	22.5 ab	7.3 ab	15.0 ab
Neem	25.3 b	44.4 b	19.8 b	36.4 ab
Dimlin	29.0 c	40.0 b	18.0 ab	27.5 ab
Check	45.0 d	72.5 c	34.3 c	70.0 c

[a] Means in columns with different letters are significantly different; alpha = 0.05.

Table 3—Mean percent top-whorl and terminal shoot infestation for group testing in 1996

	Experiment 2: AL Coastal Plain		Experiment 2: GA Piedmont	
Product	Top whorl	Terminal	Top whorl	Terminal
Capture	4.0 a[a]	3.0 a	0.0 a	0.0 a
Tempo	1.4 a	0.0 a	1.1 a	0.0 a
Pounce	5.2 a	3.0 a	0.8 a	0.0 a
Foray	2.8 a	7.0 a	5.6 ab	3.4 a
Foray plus UV	6.6 a	3.0 a	9.6 b	20.6 b
Mimic	5.0 a	7.0 a	2.4 ab	4.0 a
Orthene	10.0 a	7.0 a	11.1 b	16.8 b
Orthene II	NA	NA	3.1 ab	10.2 b
Orthene/ tame	6.0 a	3.0 a	6.7 ab	4.0 a
Orthene/tame II	NA	NA	3.5 ab	6.6ab
Check	24.0 b	23.0 b	26.9 c	50.0 c

[a] Means in columns with different letters are significantly different at alpha = 0.05.

Table 4—Mean percent top-whorl and terminal shoot infestation for group testing in 1996

	Experiment 2: VA Coastal Plain
Product	Top whorl shoots
Capture	13.8 a[a]
Tempo	18.3 ab
Pounce	23.5 ab
Foray	31.0 ab
Foray plus UV	24.2 ab
Mimic	24.0 ab
Orthene	35.7 b
Orthene II	32.5 b
Orthene/Tame	35.0 b
Orthene/Tame II	27.3 ab
Check	64.5 c

[a] Means in columns with different letters are significantly different at alpha=0.05

top whorl infested shoots (F=19.2, P<0.001, n=4, df=5) (table 5). Infestation levels were held below 10 percent in top whorl shoots except for a Tame® application on spray date 2. Orthene®, Mimic®, and Foray® all of which are thought to have optimum spray dates occurring after the predicted pyrethroid date, showed good residual efficacy based on their early application dates. Mild temperatures during the early spring and reduced UV incidence due to the oblique angle of the sun may contribute to this apparent increase in residual efficacy. Applications made later in the year may not demonstrate this phenomena. In efficacy tests conducted in the upper Coastal Plain of Georgia during the third generation of NPTM, Warrior®-treated plots had less than 2 percent infestation in top whorl shoots compared to 4 percent for Pounce® and 26 percent for the untreated controls (F=51.2,P<0.001, n= 4, df=2) (fig. 1). Fourth generation control was excellent given the strongly asynchronous nature of tip moth brood at this time of year, plus the fact that the application rate for Warrior® was inadvertently cut in half (fig. 2). Infestation level was held to 4 percent in top whorl shoots compared with 18 percent for Pounce® and 35 percent for untreated controls (F=18.7, P<0.001, n=5, df=2).

Table 5—Mean percent top-whorl and terminal shoot infestation for group testing in 1997

	Experiment 3: AL Coastal Plain			
	Spray date 1		Spray date 2	
Product	Top whorl	Terminal	Top whorl	Terminal
Orthene	0.7 a[a]	4.1 a	1.0 a	0.0 a
Pounce	3.2 ab	13.7 a	4.7 ab	6.8 a
Mimic	4.2 ab	6.2 a	6.3 ab	2.0 a
Foray	7.3 b	32.5 b	10.0 bc	9.3 a
Tame	7.5 b	6.6 a	14.7 c	17.5 b
Check	26.3 c	51.1 c	32.5 d	36.7 c

[a] Means in columns with different letters are significantly different at alpha = 0.05.

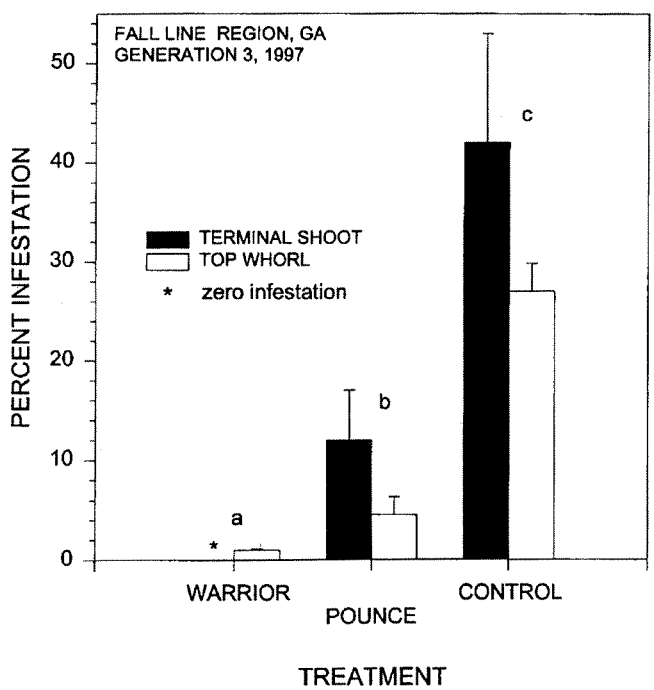

Figure 1—Mean percent infested shoots for Warrior and Pounce treated pines on a Georgia upper Coastal Plain site in summer of 1997.

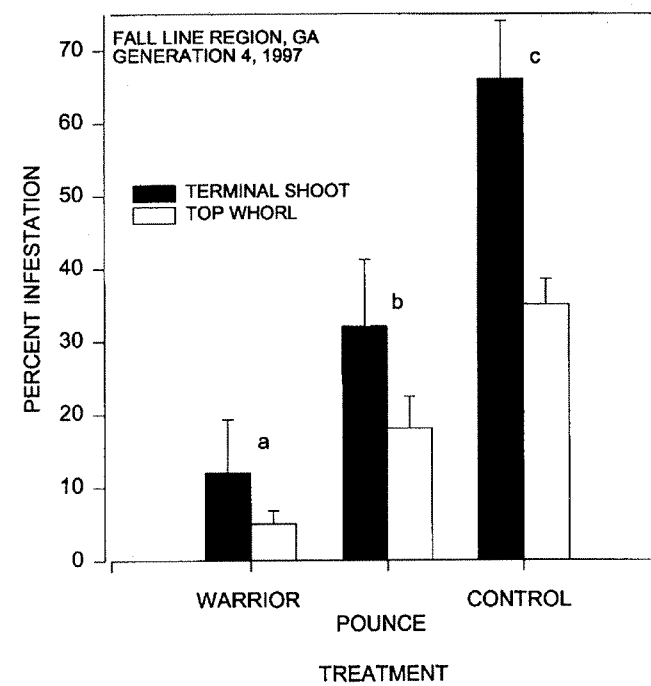

Figure 2—Mean percent infested shoots for Warrior and Pounce treated pines on a Georgia upper Coastal Plain site in late summer of 1997.

Experiment 4 (1998):

The site in the Georgia Piedmont near Lexington experienced moderate to heavy tip moth infestation in 1998 with the untreated control plots having near 50 percent infestation in the top whorl shoots (fig. 3). Both rates of Imidan® provided excellent control, being significantly better than both Pounce® and untreated control plots (H=15.9,P=0.001, n=5, df=3;). The low dosage rate of Imidan® in this trial was very efficacious, and the results warrant additional testing of this product at lower rates.

CONCLUSIONS

There are several chemical control options in a variety of chemical classes for reducing damage by NPTM. Simple but adequate timing models are available for most commercial pine growing regions and can probably be extrapolated to areas not specifically covered by recent and current research. Resistance management should be easily accomplished by timing sprays and rotating chemicals when necessary. Forestry benefits greatly from agricultural testing of new products. Target specificity and toxicological data are generally available 5–10 years before a new product is considered for forestry use. Given this, we do not foresee a lack of products in the near future for inclusion in a NPTM management program. The real challenge lies in assessing the need to spray, and maximizing application efficacy once the decision is made to use an insecticide.

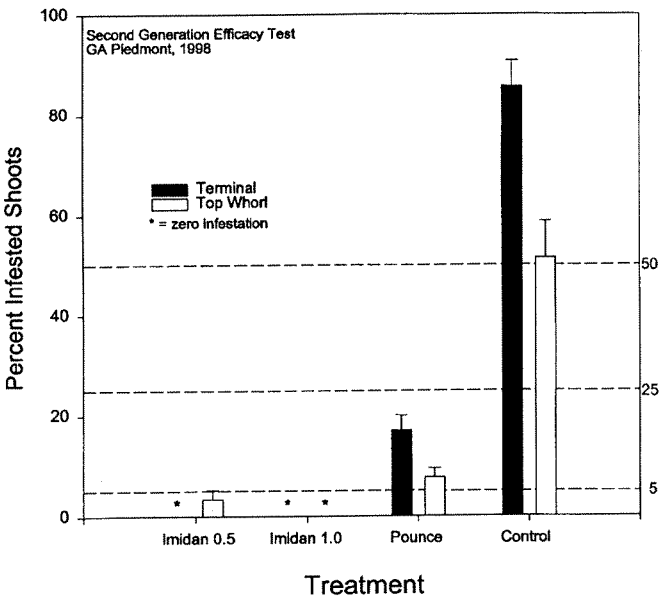

Figure 3—Mean percent infested shoots for two rates of Imidan and one of Pounce treated pines on a Georgia Piedmont site in summer of 1998.

ACKNOWLEDGEMENTS

We would like to thank International Paper Company personnel, in particular Scott Cameron and Jimmy Seckinger, for their invaluable assistance in locating sites for spray testing.

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MAXIMIZING PINE TIP MOTH CONTROL: TIMING IS EVERYTHING

Christopher J. Fettig[1]

INTRODUCTION

The impact of the Nantucket pine tip moth, *Rhyacionia frustrana* (Comstock), has become of increasing concern as standard silvicultural practices have intensified in southern pine production. The associated silvicultural manipulations of site preparation, herbaceous weed control, release, bedding and fertilization have shortened rotation lengths and increased volume yields (Nowak and Berisford 2000), but have often elevated tip moth infestation levels (Nowak and Berisford 2000, Ross and others 1990). As a result, insecticide applications are now being considered as part of silvicultural prescriptions for intensively-managed pine plantations.

There are several insecticides registered for controlling tip moth infestations in forest plantations. The difficulty is that the availability of these compounds tends to fluctuate as older materials lose their registration (i.e., some organophosphates) and new compounds expand their labels to include forest plantations (i.e., spinosad). Therefore, a complete listing of registered insecticides is not provided here, but can easily be located in a current pest control handbook distributed by State Cooperative Extension offices.

Direct control with contact insecticides is effective if properly timed to target susceptible life stages of the pest. Timing is critical due to the non-systemic, relatively short residual nature of most insecticides currently registered for tip moth control. Spraying insecticides at about 30–80 percent egg hatch maximizes control, and corresponds with an abundance of first and second instar larvae exposed on infested shoots (Berisford and others 1984, Gargiullo and others 1985, Kudon and others 1988). These stages are most susceptible to control due to their small size, presence on the tree surface, and movement over sprayed areas when searching for new feeding sites. Insecticide applications should therefore target these life stages to maximize efficacy.

Several spray timing models are available to meet these objectives (table 1), and there continues to be a gradual evolution in the development of models for specific compounds and locations. Berisford and others (1984) first identified the need for spray timing as a way of reducing application frequencies in Georgia Christmas tree plantations. The first biological timing schedules were developed for dimethoate (Cygon®) and esfenvalerate (Pydrin®) insecticides using degree-day accumulations to predict optimum spray dates in the Georgia Piedmont (Gargiullo and others 1983) and Coastal Plain (Gargiullo and others 1985). In general, the procedure involves accumulating degree-day summations commencing on the date of first catch in pheromone-baited traps for each generation, and continuing until an experimentally determined sum is attained. This sum indicates the optimal spray date for each generation and is based on moth phenology. Most published models are based on variations of this theme with spray prediction values being derived from moth phenology distributions or insecticide spray timing trials (table 1).

Although largely effective, improper use of spray timing models has occasionally led to errors in spray date predictions. These models require a detailed knowledge of tip moth biology, proper pheromone trap deployment, intensive trap monitoring, knowledge of degree-day calculations, conversions and utility, and the ability to acquire daily maximum and minimum temperatures on or near the site. Scheduling problems may still arise from short-term advance notice of approaching spray dates or inclement weather patterns that limit insecticide spray opportunities. The development of an efficient method that permits prediction of spray dates in the absence of spray timing models is highly desirable.

PREDICTIONS OF OPTIMAL SPRAY DATES FROM LONG-TERM WEATHER RECORDS

Procedures

Mean maximum and minimum temperatures for each day of the year were obtained for selected weather stations in Virginia (n = 49), North Carolina (n = 58), South Carolina (n = 45), Georgia (n = 70), Alabama (n = 54), Mississippi (n = 52), and northern Florida (n = 26). Daily mean maximum and minimum temperatures for each weather station were placed in a spreadsheet program (Microsoft Excel, Microsoft Corp., Seattle, WA), and then transferred to a degree-day computational program (Degree-Day Utility, University of California Statewide Integrated Pest Management Program, Davis, CA). Degree-days were accumulated using the single-sine, intermediate cutoff computation method (Seaver and others 1990) with lower and upper developmental thresholds of 9.5 and 33.5 °C, respectively (Haugen and Stephen 1984). The annual number of degree-days accumulated at each station was divided by 754 degree-days °C (the minimum required for completion of a single generation) and rounded to the next lowest whole number to provide an estimate of the number of tip moth generations occurring annually at that location (Ross and others 1989). The weather station locations and the numbers of corresponding generations were then mapped for each state.

[1] Postdoctoral Research Associate, 413 Biological Sciences Building, Department of Entomology, The University of Georgia, Athens, GA 30602.

Citation for proceedings: Berisford, C. Wayne; Grosman, Donald M., eds. 2002. The Nantucket pine tip moth: old problems, new research. Proceedings of an informal conference, the Entomological Society of America, annual meeting. 1999 December 12–16. Gen. Tech. Rep. SRS–51. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 68 p.

Table 1—Papers published on the timing of insecticide applications for controlling tip moth infestations

Authors	Title	General description
Gargiullo and others 1983	How to time dimethoate sprays against the Nantucket pine tip moth	Spray timing model using pheromone-trap data and degree-day summations for a 3 generation phenology in the Georgia Piedmont
Berisford and others 1984	Optimum timing for insecticidal control of the Nantucket pine tip moth	Non-systemic chemical control must be directed toward early developmental stages
Gargiullo and others 1984	Mathematical description of Rhyacionia frustrana (Lepidoptera: Tortricidae) cumulative catches in pheromone traps, cumulative eggs hatching, and their use in timing of chemical control	Spray timing model for a 3 generation phenology in the Georgia Piedmont and validated and refined in Oklahoma and North Carolina
Gargiullo and others 1985	Prediction of optimal timing for chemical control of the Nantucket pine tip moth in the southeastern coastal plain	Spray timing model using pheromone-trap data and degree-day summations for a 4 generation phenology in the Georgia Coastal Plain
Kudon and others 1988	Refinement of a spray timing technique for the Nantucket pine tip moth (Lepidoptera: Tortricidae)	Two insecticide applications were necessary for adequate control of the third generation in the Georgia Piedmont
Malinoski and Paine 1988	A degree-day model to predict Nantucket pine tip moth flight in southern California	Prediction of optimum spray dates using trap catch data and a degree-day flight model for control of a 4 generation phenology in California
Pickering and others 1989	An automated system for timing insecticidal sprays for Nantucket pine tip moth control	Automated computer system that provided daily predictions of optimal spray dates for 70 stations in Georgia (obsolete)
Richmond 1992	Timing sprays by a heat unit model of spring flight of the Nantucket pine tip moth in North Carolina	A spray timing model developed for North Carolina
Fettig and others 1998	Revision of a timing model for chemical control of the Nantucket pine tip moth (Lepidoptera: Tortricidae) in the southeastern coastal plain	Corrected spray timing values are reported for data initially provided by Gargiullo and others 1985
Fettig and Berisford 1999	Nantucket pine tip moth phenology in eastern North Carolina and Virginia: implications for effective timing of insecticide applications	Spray timing model using trap catch data and degree-day summations for a 3 generation phenology in eastern North Carolina and Virginia
Fettig and others 2000a	Nantucket pine tip moth (Lepidoptera: Tortricidae) phenology and timing of insecticide applications in seven southeastern states	Optimal spray periods are provided for locations (354) with either 3 or 4 generation phenologies in the southeastern U.S.A. Allows for surprisingly accurate timing without using spray timing models
Fettig and others 2000b	Effects of Nantucket pine tip moth insecticide spray schedules on loblolly pine seedlings	An optimal insecticide spray schedule is identified that eliminates four sprays over a two year period when compared to standard applications
Nowak and others 2000	Efficacy tests and determination of optimal timing values to control Nantucket pine tip moth (Lepidoptera: Tortricidae) infestations	Optimal spray timing values are provide for permethrin, lambda-cyhalothrin, spinosad, and *Bacillus thuringiensis* Berliner in the Georgia piedmont

The length of winter diapause and the precise conditions required to break it are unknown for the Nantucket pine tip moth, and temperatures above the lower developmental threshold may occur throughout the year. Therefore, spray timing prediction values were accumulated from an arbitrarily established biofix of 7 January where four generations occur annually and 1 March where three generations occur annually. These dates are based on the time of average male moth emergence for the first generation. Three different sets of spray timing values were used to predict optimal spray dates. In portions of Virginia and North Carolina where three generations occur annually the values were 188, 784, and 1472 degree-days °C (Fettig and Berisford 1999). In remaining portions of the Southeast where three generations occur annually the values were 204, 968, and 1787 degree-days °C (Fettig and Berisford 1999). In locations where four generations occur annually the values were 237, 899, 1757, and 2513 degree-days °C (Fettig and others 1998). Spray timing values are not available for controlling populations with two or five annual generations and therefore are not provided for such locations. Degree-days were accumulated continuously for each weather station from the assigned biofix until the appropriate spray prediction value was reached for each generation. The corresponding date was designated the optimal spray date. Each optimal spray date was then located in an optimal spray period established by dividing the calendar year into 5-day increments.

To test the validity of spray period predictions, the predictions were compared to 44 spray dates determined at 16 different field sites during 1996–1998. The field-determined spray dates were calculated on site by monitoring moth flight with pheromone-baited sticky traps (Pherecon 1 C; Trece Inc., Salinas, CA) and accumulating degree-day totals using continuously recording biophenometers (Model TA51; Dataloggers Inc., Logan, UT). During this period, mean temperatures were generally normal (1996), below normal (1997), and above normal (1998) (Athens, GA June departure from normal: -0.06 °C, -2.33 °C, and 2.06 °C, respectively) throughout most of the Southeastern U.S.A.

Results and Discussion

Our phenology predictions indicated the moth would complete two to five generations annually in this region. Two generations occurred throughout the Mountain Province in Virginia and North Carolina and at some of the highest elevations of South Carolina and Georgia. Three generations occurred throughout the Piedmont Plateau and in the Coastal Plain of Virginia and parts of North Carolina. Four generations occurred in much of the remaining portions of the Coastal Plain to a northern limit apparently located in Craven County, North Carolina. Five generations were predicted for extreme southern portions of Alabama, Georgia and Mississippi, and in northern Florida.

Table 2 provides a brief example of how the optimal spray periods predictions are to be utilized. For example, if you wish to control tip moth in a pine plantation in the vicinity of Athens, GA with a pyrethroid insecticide, you would initially find the nearest weather station located to your vicinity on the maps provided in the original publication (see Fettig and others 2000a). After finding this location as site 7, you would look up site 7 on table 2. The optimal spray periods for this site are predicted for 16–20 April, 20–24 June, and 4–8

Table 2—Site number, location, and optimal spray period predictions for 15 weather stations located throughout Georgia

		Spray period			
No.	Location	1	2	3	4
1	Albany	March 17–21	May 21–25	July 10–14	Aug 19–23
2	Alma	—[a]	—	—	—
3	Alpharetta	April 21–25	June 30–July 4	Aug 24–28	
4	Americus	March 22–26	May 26–30	July 15–19	Aug 29 –Sept 2
5	Appling	April 11–15	June 20–24	Aug 9–13	
6	Ashburn	March 27–31	May 26–30	July 15–19	Aug 29 –Sept 2
7	Athens	April 16–20	June 20–24	Aug 4–8	
8	Atlanta	April 16–20	June 15–19	Aug 4–8	
9	Augusta	April 1–5	May 31–June 4	July 20–24	Sept 3–7
10	Bainbridge	March 12–16	May 21–25	July 10–14	Aug 19–23
11	Blairsville	—	—	—	—
12	Brunswick	—	—	—	—
13	Byron	April 1–5	June 5–9	July 25–29	Sept 8–12
14	Calhoun	April 16–20	June 25–29	Aug 14–18	
15	Camilla	—	—	—	—

[a] "—" refers to spray periods that are not applicable to spray timing because models have not been developed for populations with 2 or 5 annual generations.

August, and therefore treatments should be applied during these intervals. The lack of data in the column labeled spray period four indicates only three annual generations occur at this location.

Fourteen (31.8 percent) of the predicted spray periods agreed with field-determined spray dates, 21 (47.7 percent) differed by one spray period (i.e., a five day arbitrarily established interval), six (13.6 percent) differed by two spray periods, and three (6.8 percent) differed by three spray periods. Six (66.7 percent) of the spray predictions that differed by two or three periods occurred during the first tip moth generation and may reflect discrepancies between the arbitrary biofix date and the actual initiation of moth flight at these locations.

Spray timing values are typically determined experimentally by applying insecticide sprays at specified degree-day intervals, assessing damage levels for each spray, and using second degree polynomial regressions (parabolas) to determine optimal spray timing values. Although an optimal value exists, approximately 125 degree-days surround the optimal value in which little or no variation in damage levels is observed (from Gargiullo and others 1985). Assuming a typical mean daily temperature of 15.5 °C for the first generation, 20.5 calendar days of thermal units would occur during the 125 degree-day interval. In all cases, our predictions will meet this criterion. However, it also shows why spray timing becomes more critical in later generations. Assuming a mean daily temperature of 26.7 °C, the same 125 degree-day interval represents only 7.3 days of thermal units. Under these circumstances, our predictions would be effective 87 percent of the time.

EFFECTS OF INSECTICIDE SPRAY SCHEDULES ON LOBLOLLY PINE SEEDLING YIELDS

We are currently able to time insecticide applications accurately within a generation using either spray timing models or the optimal spray periods that were discussed above. However, it may not be necessary to treat each and every tip moth generation for the first two or three years following stand establishment as is the common convention. The objective of this study was to develop a tip moth control program that maximizes yield in loblolly pine, *Pinus taeda* L., with the minimum number of insecticide applications during the first two years following stand establishment (Fettig and others 2000b).

Procedures

In 1997, two newly-planted (1-yr old) and two 2-yr old plantations were selected as study sites in the Georgia Piedmont. Three randomized complete blocks were established in each plantation. Each block consisted of eight randomly assigned plots corresponding with the number of treatments and contained 12 randomly selected trees (N = 1152). In 1998, three additional 1-yr old and four additional 2-yr old plantations were selected as study sites in the Georgia Piedmont and North Carolina and Virginia Coastal Plain. Five randomized complete blocks were established in each plantation. Each block contained eight plots and eight randomly selected trees within a plot (N = 2560). All sites had received herbaceous weed control and were planted with 1-0 loblolly pine seedlings. It was previously confirmed that three tip moth generations occurred in each region.

The timing of insecticide applications was determined by monitoring male moth emergence for each generation with sex pheromone lures in Pherocon 1 C sticky traps (Trece Inc., Salinas, CA), and accumulating degree-days after the detection of an average of one moth per trap per day using continuously recording biophenometers (Omnidata T151; Dataloggers Inc., Logan, UT). Insecticides were applied at 188, 261 and 315 degree-days °C in North Carolina and Virginia, and 204, 308 and 293 degree-days °C in Georgia for each of the three tip moth generations (Fettig and Berisford 1999).

Applications included timed sprays of permethrin (Pounce 3.2 EC) with hand-pump backpack sprayers (Model 425; Solo™, Newport News, VA) at a rate of 0.6 ml of formulated product per liter of water. Treatments consisted of all possible combinations of insecticide spray schedules based on three annual tip moth generations, specifically: C) untreated control, 1) first generation, 2) second generation, 3) third generation, 1&2) first and second generation, 1&3) first and third generation, 2&3) second and third generation, and A) all generations. Applications were made during the first year only at three sites, second year only at six sites, and both the first and second year following stand establishment at two sites.

Damage estimates were taken on 30 randomly selected trees in Treatments C (untreated control) and A (all generations) for each site during the pupal stage of each generation. The total number of shoots (i.e., > 10 linear cm of apical stem containing foliage) and number of infested shoots were recorded in the terminal plus top whorl of each tree to assess insecticide efficacy. Growth statistics were taken in November 1997 and 1998 on each tree. Basal diameter (D) was measured with a caliper at 2.5 cm above ground surface. Height (H) was measured from the root collar to the tip of the terminal leader using a cm graduated height stick. These values were later used to compute a volume index (D^2H) for each treatment. The growth data were analyzed as a randomized complete block design and compared with the Tukey test for separation of treatment means (Sokal and Rohlf 1995).

Results and Discussion

Insecticide efficacy in both 1 and 2-yr old stands decreased throughout the year from 90.4 percent control in the first generation to 77.6 percent and 55.5 percent control in the second and third generations. Decreasing spray efficacy is commonly observed as the year progresses due to increasing asynchrony among susceptible life stages in later generations (Fettig and others 1998). Control of the first tip moth generation when insecticide efficacy is highest is also of particular importance in resistance management by limiting the proportion of insects that escape sub-lethal exposures.

Few significant differences were observed among treatment means when insecticides were applied to age 1 trees. Treatment A had significantly larger volume estimates than the untreated control. No other significant differences were

observed among the remaining treatment means. This suggests that spraying tip moth infestations only during the first year following stand establishment is ineffective unless every generation is included in the control schedule. We observed a 63.1 percent increase in volume index by applying Treatment A.

More significant differences were observed among treatment means when insecticides were applied to age 2 trees. Treatment 1&3 (generations 1 and 3), Treatment 2&3 (generations 2 and 3) and Treatment A had significantly larger diameter, height and volume estimates than the untreated control. No significant differences were observed among Treatments 1&3, 2&3 and A. At least two insecticide sprays were required to produce a significant difference in all three growth measurements. An optimal insecticide spray schedule for controlling tip moth infestations in age 2 trees with insecticide applications applied during the second year includes either spraying the first and third or second and third generations thereby eliminating one spray without any significant effect on volume yield. We observed a 39.0 percent increase in volume by applying Treatment 1&3, and a 38.9 percent increase in volume by applying Treatment 2&3.

Significant differences were observed among treatment means when insecticides were applied to the same trees at both age 1 and age 2. Treatment 1 (first generation only) had a significantly larger volume index than several other treatments including the control. We observed a 74.5 percent increase in volume index by applying Treatment 1 during the first two years following stand establishment. This is the largest increase in volume index observed relative in this study.

The application of timed permethrin sprays during the first generation of both the first and second year following stand establishment appears to be the optimal insecticide spray schedule. Insecticide efficacy is greatest during the first generation, and coincides with the time when recurrent growth species such as loblolly pine typically have their largest growth flush of the year (Oliver and Larson 1996). Recently, it has been confirmed that control of the first generation has an extended benefit (Coody and others 2000). This suggests that previous tip moth attacks predispose trees to heavier attacks during subsequent generations, possibly due to bud proliferation from previous attacks, changes in host physiology, or simply that females emerging from infested trees mate and deposit eggs on the same trees. Control of the first generation may also be important in reducing recruitment from adjacent stands by reducing the number of suitable oviposition sites (i.e., bud proliferation resulting from tip moth attacks) and the number or density of calling females.

Currently, most tip moth control programs target at least the first and second year following planting and insecticides are repeatedly applied to control each generation. Our data suggest that it is unnecessary to control each generation to significantly increase volume yields. The optimal insecticide spray schedule program for a three generation tip moth phenology would include a single first generation spray during the first two years following planting. This would reduce the current practice by four sprays over the two year period, which would be both economically and ecologically beneficial, two important criteria for an integrated pest management program.

CONCLUSIONS

The application of insecticides to manage tip moth infestations is likely to become more common in the future as we attempt to increase fiber production. Spray timing is critical to successfully controlling these infestations. The questions remains as to what degree of accuracy is acceptable, and how inexpensively it can be obtained.

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TIP MOTH PARASITOIDS AND PESTICIDES: ARE THEY COMPATIBLE?

Kenneth W. McCravy, Mark J. Dalusky, and C. Wayne Berisford[1]

Abstract—Effects of herbicide and insecticide applications on parasitism of the Nantucket pine tip moth, *Rhyacionia frustrana* (Comstock) were examined in 2-yr-old loblolly pine (*Pinus taeda* L.) plantations in Georgia. Total parasitism rates varied significantly among tip moth generations, but there were no differences in parasitism rates between herbicide-treated and untreated plots. Significant differences in the relative abundance of parasitoid species were found among generations, with *Eurytoma pini* Bugbee being the most common in summer and *Lixophaga mediocris* Aldrich the most abundant in spring. Plots treated with the insecticide, Orthene, had significantly less parasitism than plots treated with tebufenozide, *Bacillus thuringiensis* var. *kurstaki*, or untreated check plots. Effects of acephate treatments were species-specific, with no apparent effects on parasitism by *L. mediocris* Aldrich but significantly decreased parasitism by *Haltichella rhyacioniae* Gahan.

INTRODUCTION

Damage caused by the Nantucket pine tip moth, *Rhyacionia frustrana* (Comstock) is highly variable, and may be negligible or high enough to cause tree mortality. Large population fluctuations have been associated with common southern forest regeneration practices, which often include intensive site preparation, chemical control of competing vegetation, and fertilization to increase seedling growth (Miller and Stephen 1983, Nowak and Berisford 2000). The Nantucket pine tip moth has a high reproductive potential, which may be constrained to some degree by high parasitism rates (Eikenbary and Fox 1968a,b; Freeman and Berisford 1979; Wallis and others 1980; Gargiullo and Berisford 1983; Warren 1985; McCravy and Berisford 2000). Potential effects of forest management practices on tip moth parasitoids have received little attention. It has been suggested that natural enemies of herbivorous insects are more effective in diverse systems than in simple ones (Pimentel 1961). In a review of tests of this natural enemy hypothesis, however, Russell (1989) found the results to be inconclusive for parasitism.

Insecticidal control of tip moths may be necessary in intensively-managed commercial pine plantations. A number of "hard" pesticides such as acephate, an organophosphate, have been used successfully to control tip moth populations. However, organophosphates often cause high mortality among natural populations of parasitoids and predators as well (Croft 1990). Alternative insecticides, such as *Bacillus thuringiensis* var. *kurstaki* (Btk) and the insect growth regulator, tebufenozide, may be more compatible with tip moth natural enemies. In this paper we describe two studies investigating effects of herbicidal vegetation control and conventional and biorational insecticidal treatments on tip moth parasitism.

MATERIALS AND METHODS

Vegetation Control Study

This study was conducted in 1996–97 in three 2-yr-old loblolly pine plantations in the Georgia coastal plain. The plantations ranged from 44 to 70 ha. Two sites were located in Burke County, near Waynesboro, and one in Bulloch County, near Statesboro. Each site was mechanically prepared, and 1-0 bareroot improved loblolly pines were machine planted at densities of approximately 1492 trees per ha in the winter of 1994–95. In spring, 1996, each tract was divided approximately in half, with one randomly selected half receiving a herbicidal treatment of hexazinone and sulfometuron methyl at rates of 2.34 and 0.22 liters/ha, respectively. The remaining halves were left untreated. The Waynesboro sites were treated again in the fall, 1996 with imazapyr and glyphosate at 0.58 and 2.38 liters/ha, respectively. Herbicides were applied by helicopter at the Waynesboro sites and by tractor at the Statesboro site. In spring, 1996, 50 pines were randomly chosen in each treatment of each study site to serve as permanent study trees. Tip moth infestations were evaluated by counting numbers of infested shoots on the permanent study trees in each generation, when tip moths were in the late larval and pupal stages and damage was most obvious. Non-pine vegetation was quantified and characterized for each treatment plot as well. Twenty randomly located 1 m^2 quadrats were established in each plot at each site during each tip moth generation. For each quadrat, a visual estimate of percentage ground cover was taken, the maximum height of vegetation was measured, and presence or absence of flowering vegetation was recorded. Specimens of each plant species present were taken, returned to the laboratory, and identified to species. The spring, 1997 (1st)generation of the Statesboro site was not included in the study because of low tip moth populations.

[1] McCravy, Assistant Professor, Department of Biological Sciences, Western Illinois University, Macomb, IL 61455; Dalusky, Research Coordinator, and Berisford, Professor, Department of Entomology, University of Georgia, Athens, GA 30602.

Citation for proceedings: Berisford, C. Wayne; Grosman, Donald M., eds. 2002. The Nantucket pine tip moth: old problems, new research. Proceedings of an informal conference, the Entomological Society of America, annual meeting. 1999 December 12–16. Gen. Tech. Rep. SRS–51. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 68 p.

Collections of infested shoots for rearing of tip moths and parasitoids also were made during the late larval/pupal stages of each tip moth generation. In each treatment plot, 2,000 infested shoots were randomly collected from non-permanent study trees. Summer (2nd generation) 1996 collections were made on 26–27 June and 2–3 July at the Statesboro and Waynesboro sites, respectively. Late summer (3rd generation) 1996 shoots were collected on 7–8 August and 10–11 August, respectively. Collections of shoots for the overwintering (4th) generation were made in two stages. Half of the shoots were collected on 22 September and 26 September, 1996 at the Statesboro and Waynesboro sites, respectively, and half were collected on 16 January and 21 January, 1997. This was done in order to sample parasitoids that might emerge before the onset of tip moth pupal diapause as well as those emerging in late winter and early spring. Spring (1st generation) 1997 collections were made on 3–4 May at the Waynesboro sites. Because of low tip moth infestations for this generation, 1,000 shoots were collected from each treatment plot. Shoots were returned to the laboratory and placed in ventilated rearing containers (Berisford and others 1971), separated by site and treatment. Emerging adult moths and parasitoids were collected every 2–3 days. Moths were counted and parasitoids were counted and identified to species, if possible, using Yates' (1967) key, and placed in 70 percent EtOH. At the end of emergence for each collection, shoots were removed from the rearing cans, dissected, and examined for the presence of tip moths, parasitoids, or cocoons. Series of each apparent species were sent to appropriate taxonomic authorities for positive determinations. Tip moth parasitism rates were determined based on relative numbers of emerged parasitoids and moths. Two parasitoids, *Hyssopus rhyacioniae* Gahan and *Pteromalus* sp. Swederus, were determined to be gregarious based on dissection of individual tip moth-infested shoots, and averaged 12.2 $\pm$ 1.20 (mean $\pm$ SEM, n = 15) and 2.92 $\pm$ 0.45 (n = 12) individuals per brood, respectively. Total numbers of individuals reared for these two species were divided by these means to get a more realistic estimate of the number of parasitism events.

Parasitoids were also collected using malaise traps in order to get an estimate of the relative abundances of parasitoids in the herbicide-treated and untreated plots. Two traps, one in each treatment plot, were operated at the Waynesboro 1 and Statesboro sites for eight five-day trapping periods from mid-June to early October 1996. Traps were randomly relocated for each trapping period. Insects were collected in 70 percent EtOH. At the end of each trapping period, samples were taken to the laboratory and parasitoids, defined as Parasitica (Huber 1993) plus tachinids (Diptera), were removed and counted. Recognizable tip moth parasitoids were also separated and counted.

Numbers of infested shoots and parasitism rates were each compared between treatments and among generations and sites using 3-way analysis of variance, with Tukey's multiple comparisons test. Relative variation in infestation levels and parasitism rates for each treatment, pooled across site and generation, was measured using the coefficient of variation (Sokal and Rohlf 1995). Comparison of proportions of *H. rhyacioniae* reared from tip moth-infested shoots collected from herbicide-treated vs. untreated plots was made using paired *t*-tests. Numbers of parasitoids captured in malaise traps were compared between treatments and sites using 2-way analysis of variance. All analyses were performed using the SigmaStat Version 2.0 software package (Jandel Scientific Software 1995).

Insecticide Study

This study was conducted in a 2-yr-old loblolly pine plantation, of approx. 80 ha, in Taylor Co., GA. Pines ranged from 0.6 m to 1.2 m in height. Tip moth populations were high, with a shoot infestation rate of approx. 66 percent in the top whorl of branches for the 1st generation. Sprays were timed for optimum efficacy with a degree-day timing model developed using an organophosphate insecticide (dimethoate) for the Nantucket pine tip moth (Garguillo and others 1985). Moth flight was monitored with four wing traps (Pherocon 1C® baited with Nantucket pine tip moth lures (Trece Inc., Salinas, CA). Upon initiation of the summer (2nd) tip moth generation, degree-days were accumulated with a continuously recording biophenometer.

The study was set up as a randomized complete block design, with two replicates (blocks) per treatment and untreated control, for a total of eight plots. Plots were rectangular and 2.8 ha. Blocks were approximately 30 m apart, and plots were a minimum of 150 m apart. Acephate (10.8 percent [AI]), Btk (100 percent [AI]), and tebufenozide (2.0 percent [AI]) were used as treatments. Acephate and tebufenozide were applied at a rate of 4.6 liters/ha, while Btk was applied undiluted at 0.77 liters/ha.

Applications were made by helicopter with a 9.1 m air foil simplex boom and spray system. Acephate and tebufenozide were delivered at a rate of 68.9 liters/min. Btk was sprayed at 11.7 liters/min. Acephate and tebufenozide were applied on the evening of 3 June 1998. Wind speed was 0–5 km/h, and temperature and relative humidity were 30° C and 66 percent, respectively. Btk was sprayed in the early morning on 4 June 1998. Wind speed was 0–8 km/h, and temperature and relative humidity were 25° C and 99 percent, respectively. Coverage was monitored by deploying 10 water sensitive cards in each spray plot.

Insecticide efficacy was evaluated on 50 randomly selected trees in each plot by assessing percentage infestation of shoots in the top whorl after moths had reached the late larval/pupal stages, in early July. At that time, approx. 500 damaged shoots were randomly collected from the interior 1.2 ha of each plot for rearing of adult moths and parasitoids. Most tip moth parasitoids are koinobionts and emerge from late larvae and pupae of the moths. Shoots were placed in ventilated rearing containers (Berisford and others 1971). Emerging adult tip moths and parasitoids were collected weekly and stored in 80 percent EtOH.

Treatment effects on overall parasitism rates were analyzed using 2-way analysis of variance with Tukey's multiple comparison test. Variation in contribution of individual parasitoid species to overall parasitism between each treatment and control was examined using the chi-square test of independence (Sokal and Rohlf 1995). Species-specific differences were evaluated by comparing cell-

specific contributions to the overall chi-square to a critical value of 3.841, using a one-degree-of-freedom criterion at an alpha value of 0.05 (Freeman 1987). All statistical analyses were done using SigmaStat, version 2.0 (Jandel Scientific Software 1995).

RESULTS

Vegetation Control Study

The most common plant species found (during sampling months in which flowering individuals were present) are shown in Table 1. Total vegetation was greater in untreated than herbicide treated plots for all three parameters measured, pooled across site (table 2).

Percent shoot infestation was higher in the untreated plots (10.517 ± 0.958) than in the treated plots (2.992 ± 0.494) (F = 121.731; df = 1,6; $P < 0.001$). Percent shoot infestation among generations ranged from 5.372 ± 1.521 for the late summer generation to 8.703 for the winter generation, and were marginally nonsignificant (F = 4.681; df = 3,6; P = 0.052). Infestation rates among sites ranged from 5.924 ± 1.545 for the Waynesboro 1 site to 7.605 ± 2.121 for the Waynesboro 2 site, with no significant differences (F = 2.027; df = 2,6; P = 0.213) There were no significant interaction effects. Relative variation in infestation levels was much greater in treated than untreated plots (CV = 57.18 percent vs. 32.89 percent, respectively).

Mean tip moth parasitism rates were 51.0 percent ± 6.61 percent and 48.2 percent ± 6.17 percent in the herbicide-treated and untreated plots, respectively. Rates were not significantly different between treatments (F = 1.17; df = 1, 6; P = 0.321). Parasitism rates were different among sites (F = 22.91; df = 2, 6; P = 0.002) and generations (F = 92.90; df = 3, 6; $P < 0.001$). Rates were significantly higher at Statesboro than at the Waynesboro sites. Rates of parasitism were highest in the spring and summer generations and lowest in the winter (fig. 1). There were no significant interaction effects. Relative variation in parasitism rates was similar in treated and untreated plots (CV = 43.02 percent vs. 42.46 percent, respectively).

Overall, 9,629 parasitoids were reared, representing 4143.5 parasitism events and 19 species in nine families. Three parasitoids, *Lixophaga mediocris* Aldrich, *Eurytoma pini* Bugbee, and *Hyssopus rhyacioniae* Gahan accounted for over 70 percent of total parasitism. *Eurytoma pini* was the most abundant species in the summer, but was relatively rare in winter and spring (fig. 2). *Lixophaga mediocris* was by far the most abundant species in the spring. *Hyssopus rhyacioniae* accounted for a greater mean proportion of parasitism in herbicide-treated (19.35 percent) than untreated (11.58 percent) plots (t = 2.269, df = 10, P = 0.047).

Malaise trapping resulted in 5,550 total parasitoid captures. Mean numbers of captures per trapping period were 177.19

Table 1—Common plant species found in quadrat sampling and month in which flowering individuals were found

	Collection Date			
Family, Genus, and Species	Jun 1996	Aug 1996	Oct 1996	Apr 1997
Asteraceae				
Eupatorium capillifolium (Lamarck) Small			+	
Gnaphalium obtusifolium L.		+	+	
Solidago sp. L.			+	
Caryophyllaceae				
Cerastium glomeratum Thuillier		+		
Cyperaceae				
Cyperus retrorsus Chapman		+		
Fabaceae				
Stylosanthes biflora Britton, Sterns, and Poggenburg	+	+		
Tephrosia spicata (Walter) Torrey and Gray		+		
Hypericaceae				
Hypericum denticulatum Humboldt, Bonpland, and Kunth		+		
Liliaceae				
Smilax sp. L.	+			
Passifloraceae				
Passiflora incarnata L.	+			
Polygonaceae				
Rumex crispus L.				+
Rosaceae				
Rubus argutus Link				+
Vitaceae				
Vitis rotundifolia Michaux	+			

Table 2—Percent ground cover, maximum height, and frequency of occurrence of flowering individuals in herbicide-treated and untreated plots for four generations averaged over two (spring generation) or three (all other generations) study sites

Generation	Treatment	Ground cover	Maximum height	Frequency of flowering plants
		Percent	*Cm*	*Percent*
Summer	Treated	21.4 ± 2.6	35.2 ± 6.7	21.7 ± 3.3
	Untreated	51.3 ± 10.4	67.5 ± 16.8	40.0 ± 18.9
Late Summer	Treated	48.5 ± 3.3	58.2 ± 6.3	65.0 ± 7.6
	Untreated	71.8 ± 0.9	85.1 ± 17.8	95.0 ± 5.0
Winter	Treated	28.6 ± 9.6	60.2 ± 12.8	16.7 ± 12.0
	Untreated	60.7 ± 8.8	101.4 ± 13.2	76.7 ± 14.5
Spring	Treated	20.4 ± 5.5	23.6 ± 12.2	30.0 ± 5.0
	Untreated	49.8 ± 8.8	62.9 ± 7.9	70.0 ± 5.0
Totals	Treated	30.6 ± 4.4	46.2 ± 6.2	33.6 ± 7.1
	Untreated	59.2 ± 4.4	80.7 ± 7.4	70.5 ± 8.7

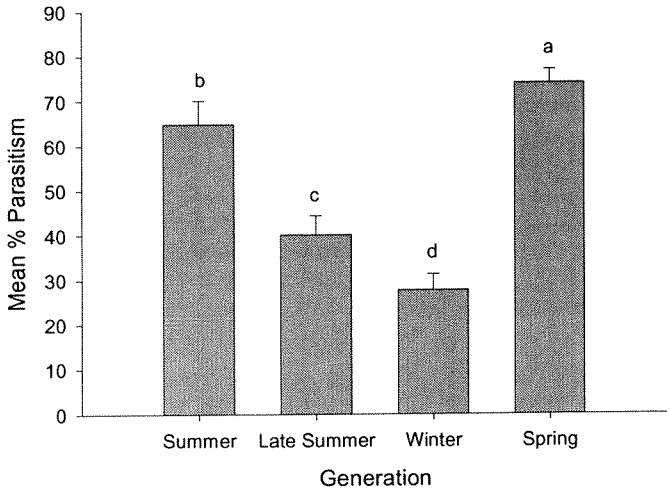

Figure 1—Mean percent tip moth parasitism (± SE) for four generations in the southeastern Georgia coastal plain. Means with the same letter are not significantly different ($P < 0.05$, Tukey's multiple comparison test).

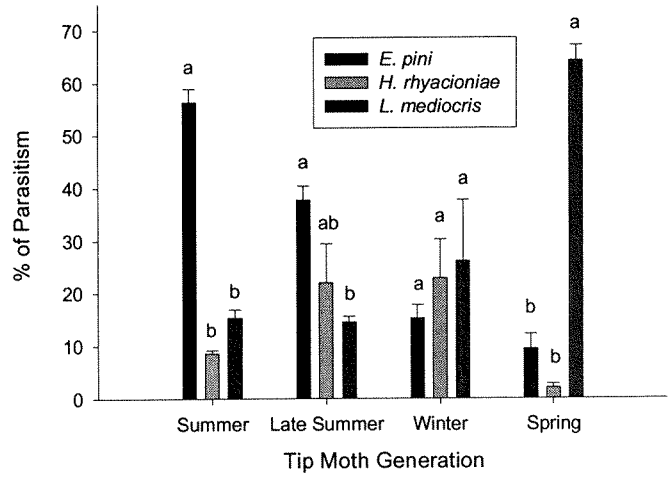

Figure 2—Mean percent of total tip moth parasitism (± SE) due to three parasitoid species for four generations in the southeastern Georgia coastal plain. Means with the same letter within a generation are not significantly different ($P < 0.05$, Tukey's multiple comparison test).

± 32.08 in the herbicide-treated plots and 169.69 ± 22.67 in the untreated plots, pooled across site, and did not differ between treatments or sites ($F = 0.0345$; df = 1,28; $P = 0.854$ and $F = 0.407$; df = 1,28; $P = 0.529$, respectively). A total of 252 known *R. frustrana* parasitoids were captured. Mean numbers captured per trapping period were 8.56 ± 1.73 in the herbicide-treated plots and 7.19 ± 1.20 in the untreated plots, pooled across site. There were no differences in captures between treatments ($F = 0.403$; df = 1,28; $P = 0.531$) or sites ($F = 0.333$; df = 1,28; $P = 0.568$). *Lixophaga mediocris* (70 percent of total) and *E. pini* (14 percent of total) were the most common species captured.

Insecticide Study

Mean percent tip moth infestations in the top whorl of shoots were 48.2 ± 3.11, 29.55 ± 5.59, 33.25 ± 8.27, and 34.85 ± 8.27 for the control, acephate, tebufenozide, and Btk plots, respectively. A total of 465 parasitoids and 723 adult tip moths were reared, for a parasitism rate of 39.14 percent. Parasitism rates differed significantly among treatments ($F = 19.601$: df = 3,3; $P = 0.018$) (fig. 3). The parasitism rate in the acephate treated plots was about half that in the check, Btk, and tebufenozide plots. There were no significant differences among the check and the latter two treatments.

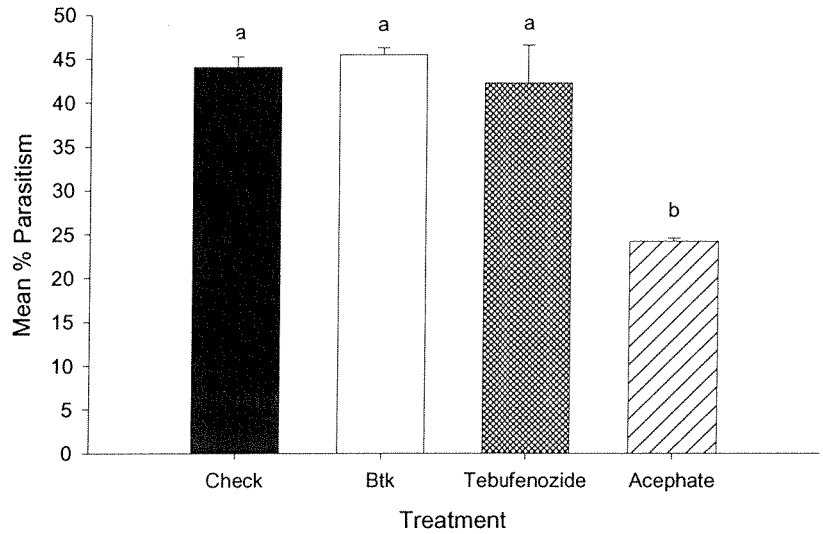

Figure 3—Mean percent tip moth parasitism (± SE) in three insecticide-treated *P. taeda* plots and an untreated check plot. Means with the same letter are not significantly different ($P < 0.05$, Tukey's multiple comparison test).

Fourteen species of parasitoids were reared. Of these, *E. pini*, an undescribed species of *Temelucha* Foerster (Hymenoptera: Ichneumonidae), *Haltichella rhyacioniae* Gahan (Hymenoptera: Chalcididae), and *L. mediocris* were the most abundant species, accounting for 89.9 percent of the total. Relative proportions of parasitism attributable to these four species differed significantly ($X^2 = 22.22$; df = 3; $P < 0.001$). This difference was primarily due to fewer *Ha. rhyacioniae* than expected ($X^2 = 3.993$; df = 1; $P < 0.05$) and more *L. mediocris* than expected ($X^2 = 8.681$; df = 1; $P < 0.005$) in the acephate treatment plots (fig. 4).

DISCUSSION

Jervis and others (1993) found plants in the families Umbelliferae and Compositae to be the most frequently visited by parasitic Hymenoptera. Among the common plants found in our study, none were Umbellifers, but three (*Eupatorium capillifolium* (Lam.) Small, *Gnaphalium obtusifolium* L., and *Solidago* sp. L.) were composites (Asteraceae, table 1). In a study of flower associations of *Scambus buolianae* (Hartig) (Hymenoptera: Ichneumonidae), a parasitoid of the European pine shoot moth, *R. buoliana* (Schiffermüller), Leius (1963) found that

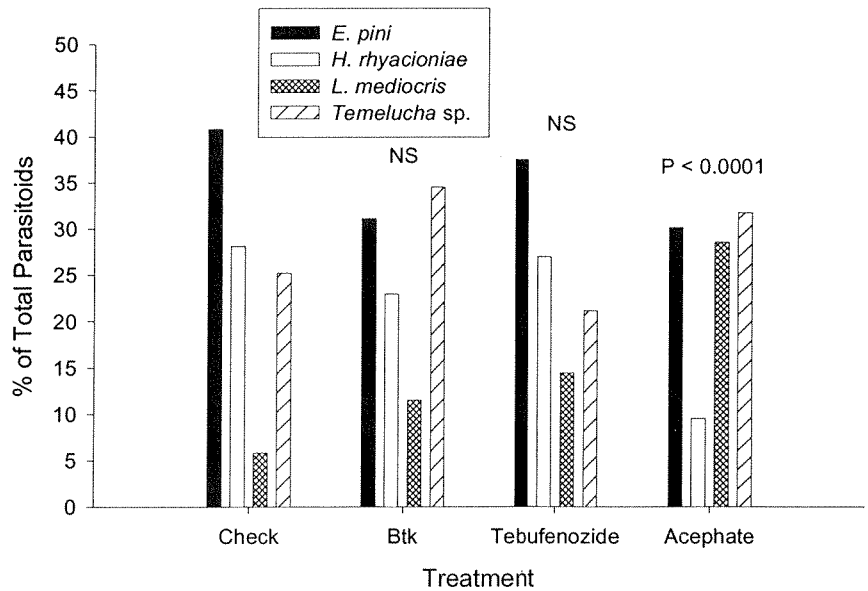

Figure 4—Relative proportions of tip moth parasitism due to four parasitoid species in three insecticide-treated *P. taeda* plots and an untreated check plot. NS = not significant.

wasps fed pollen of *S. canadensis* L. lived significantly longer than control wasps fed a sucrose solution. Likewise, Syme (1975) found increased longevity of female *Hyssopus thymus* Girault (Hymenoptera: Eulophidae) which had been exposed to the plants *Rumex acetosella* L. (Polygonaceae) and *Hypericum perforatum* L. (Hypericaceae), with exposure to *R. acetosella* also increasing fecundity. These results suggest that *R. crispus*, *H. denticulatum*, and *Solidago* sp. found in our study are potentially important food sources for *R. frustrana* parasitoids.

Past studies have found intensive forest management practices to be associated with increased tip moth population fluctuations (Miller and Stephen 1983, Nowak and Berisford 2000). Our study supported these results, with infestation levels nearly twice as variable in treated plots than in untreated plots, based on the coefficient of variation. Further study is needed to verify this association and to examine possible underlying causes.

The overall tip moth parasitism rate of ca. 50 percent found in the vegetation control study generally agrees with those of Freeman and Berisford (1979) (42 percent) for the Georgia piedmont and Eikenbary and Fox (1965) (41 percent) for the South Carolina coastal plain, but is higher than that obtained by the latter authors for the South Carolina piedmont (26.0 percent). Among individual species, *Hy. rhyacioniae* accounted for a significantly greater proportion of parasitism in the herbicide-treated than the untreated plots. This species may be less affected by microclimatic influences than the others, or may be less subject to competition or predation in the herbicide-treated plots. Tip moth infestation rates were about 3.5 times higher in the untreated plots than in the treated plots, but there was no significant difference in parasitism rates between treatments, indicating that more parasitism events occurred in the untreated plots. Malaise trapping showed no difference in parasitoid abundance between plots, suggesting a greater number of moths parasitized per parasitoid in the untreated plots, a functional response first described by Holling (1959). This response could result from greater longevity of parasitoids due to more food resources, less searching time per host due to higher moth densities, or other factors. However, the much higher infestation levels in the untreated stands suggest that vegetation management practices do not necessarily affect the role of parasitoids in tip moth population control.

The biological insecticides Btk and tebufenozide appeared to have no effect on tip moth parasitism. The effects of acephate were species-specific, with decreased parasitism by *Ha. rhyacioniae* and relatively high parasitism by *L. mediocris*. *Lixophaga mediocris* is a primary tip moth parasitoid (Freeman and Berisford 1979). Generally, *Lixophaga* spp. parasitize stem borers by ovipositing at openings made by the host. Larvae burrow through the host's frass and actively search for the host (Wood 1987). This suggests that *L. mediocris* attack late instar tip moth larvae, otherwise its eggs and larvae would be susceptible to early application of a contact insecticide such as acephate. *Lixophaga mediocris* adults are much larger and more robust than adults of the three common parasitic wasps captured in this study; this suggests that adults may be more capable of surviving contact with insecticides because of less surface to volume ratio. *Lixophaga mediocris* has been found to be most abundant in overwintering and spring tip moth generations in the Georgia coastal plain (McCravy and Berisford 2000). Thus, acephate would probably have less of an impact on overall tip moth parasitism during these generations.

Haltichella rhyacioniae has been found to be a primary parasitoid of tip moths in most studies, although one individual was reared from *L. mediocris* by Freeman and Berisford (1979). The low numbers of *Ha. rhyacioniae* in acephate-treated plots suggest that this parasitoid may be susceptible to this insecticide, either in the adult stage or perhaps as a result of larval mortality if it attacks tip moths in the early (targeted) larval stages. *Haltichella rhyacioniae* are small chalcidids, from 2.8 to 3.6 mm in length (Yates 1967), and their small size may contribute to their vulnerability to acephate. The timing of attack of *Ha. rhyacioniae* is unknown. This parasitoid is usually not a numerically important part of the tip moth parasitoid fauna, accounting for less than 10 percent of tip moth parasitism in most regions (Eikenbary and Fox 1965, Freeman and Berisford 1979, Lashomb and others 1980, Miller and Stephen 1983, McCravy and Berisford 2000), so high mortality of this species might not have a great impact on tip moth parasitism. The collection of large numbers of the undescribed species of *Temelucha* was surprising, given the numerous rearings of tip moth parasitoids done throughout much of the moth's range. This suggests that the species composition of the tip moth parasitoid complex can vary substantially even over relatively small geographic ranges. This finding further illustrates that there is still much to be learned regarding the parasitoid complexes of even relatively well-studied and economically important forest insect pests.

Little work has been done regarding the effects of tebufenozide on parasitoids. Jacas and others (1995) found that oral doses reduced survival of *Opius concolor* Szepl. (Hymenoptera: Braconidae) in a dose-dependent manner, but had no effect on fertility. Tebufenozide treatment of Mediterranean flour moth (*Ephestia kuehniella* Zeller) (Lepidoptera: Pyralidae) eggs parasitized by *Trichogramma pretiosum* Riley (Hymenoptera: Trichogrammatidae) did not significantly increase wasp mortality but did significantly reduce subsequent parasitism by exposed females (Consoli and others 1998). Potential effects on parasitism in the field were not examined in either case. In our study neither tebufenozide nor Btk had any effect on overall parasitism rates or parasitism by individual species (figs. 1 and 2). Niwa and others (1987) also found that *B. thuringiensis* had no effect on parasitism rates nor species distribution of parasitoids of the western spruce budworm, *Choristoneura occidentalis* Freeman (Lepidoptera: Tortricidae). However, Hamel (1977) found increased larval parasitism of *C. occidentalis* by parasitoids attacking early instars and decreased parasitism by parasitoids attacking late instars and pupae. These latter results were attributed to the photonegative behavior of parasitized early instar larvae, which apparently allowed them to avoid contact with the insecticide. Tip moth larvae generally bore into a needle base immediately after eclosion, and virtually the entire immature period is spent within plant tissues (Berisford 1988). Little is known of the timing of attack by the various

tip moth parasitoids. Because first instar larvae are targeted for insecticide treatment, only those attacking eggs or first instar larvae would be subject to indirect mortality due to death of the host. Those that attack later stages would suffer little indirect mortality.

These studies further illustrate that larval/pupal parasitism (40–50 percent) is an important source of tip moth mortality. Herbicide treatments did not affect parasitism rates, and infestation rates were highest in the untreated plots, suggesting that use of herbicides does not affect the ability of tip moth parasitoids to regulate moth populations. However, the fact that total parasitism was higher in the untreated plots raises the possibility that presence of greater amounts of vegetation can benefit tip moth parasitoids. Among the insecticides, the biologicals, Btk and tebufenozide, had little or no impact on tip moth parasitoids, but were less effective in controlling tip moth than acephate. This is important since parasitism could reduce residual tip moth populations when insecticidal control is incomplete. The negative effects of acephate appear to be species-specific, meaning that overall effects on tip moth parasitism could vary from region to region depending on variation in the species composition of the tip moth parasitoid complex. In generations or regions where *L. mediocris* is the dominant tip moth parasitoid, this insecticide would probably have relatively little effect on overall tip moth parasitism.

ACKNOWLEDGMENTS

We thank R. Garland, A. Coody, N. LeCroy, J. Smith, T. Jackson, B. Dorough, M. Morrow, and D. Hart (University of Georgia) for technical assistance. J. Seckinger, S. Cameron, F. Bevan (Union Camp Woodlands Corp.) and B. Mewborn (Weyerhauser Co.) were of great help in providing study sites. K. Massengale (B and S Wood Services) applied the insecticides, and J. Ghent (USDA Forest Service) assisted with equipment calibration and monitoring of spray deposition. R. Hedden (Clemson University), D. Miller (USDA Forest Service), S. Salom (Virginia Polytechnic Institute and State University), and J. Strazanik (West Virginia University) provided helpful comments on various sections of the manuscript. B. Haynes and M. Moore (University of Georgia) provided assistance and advice with vegetation sampling and plant identifications. L. Coote (Royal Ontario Museum), C. Darling (Royal Ontario Museum), G. Gibson (Agriculture and Agri-Food Canada), E. Grissell (USDA, Systematic Entomology Laboratory), S. Heydon (University of California-Davis), J. Luhman (Minnesota Dept. of Agriculture), A. Menke (USDA, Systematic Entomology Laboratory), M. Schauff (USDA, Systematic Entomology Laboratory), A. Sharkov (Ohio State University), D. Wahl (American Entomological Institute), J. Whitfield (University of Arkansas), M. Wood (Agriculture and Agri-Food Canada), and G. Zolnerowich (Texas A&M University) provided positive identifications of parasitoids. This study was supported by the Pine Tip Moth Research Consortium and USDA Forest Service Cooperative Agreement No. 42-98-0004.

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THE POTENTIAL FOR *TRICHOGRAMMA* RELEASES TO SUPPRESS TIP MOTH POPULATIONS IN PINE PLANTATIONS

David B. Orr, Charles P.-C. Suh, Michael Philip, Kenneth W. McCravy, and Gary L. DeBarr[1]

Abstract—Because the Nantucket pine tip moth is a native pest, augmentation (mass-release) of native natural enemies may be the most promising method of tip moth biocontrol. The tip moth has several important egg, larval, and pupal parasitoids. Egg parasitoids are most effective as biocontrol agents because they eliminate the host before it reaches a damaging stage. *Trichogramma* egg parasitoids are the most important of these, and are the most commonly augmented arthropod in biocontrol programs worldwide. Inundative releases of encapsulated *Trichogramma exiguum* Pinto & Platner were evaluated for suppression of *R. frustrana* in first year loblolly pine, *Pinus taeda* L., plantations. Three releases of 328,238 ± 88,379 ♀/ha, spaced 7 d apart, were made in three 0.4 ha plots during second generation *R. frustrana* egg deposition. The quality of each release was very high in comparison with published values of biological characteristics of *T. exiguum*. Parasitism of *R. frustrana* eggs was significantly increased by 29 percent when compared to check plots, egg survival (hatching) was significantly reduced by 47 percent, and larval populations were significantly reduced 60 percent. There was no significant difference in the percentage of terminals damaged between *T. exiguum*-treated (31 ± 16 percent) and control plots (45 ± 10 percent), however, length of terminal damage was significantly lower in treated plots. The percentage of damage to top whorl shoots was significantly lower in *T. exiguum*-treated plots compared with control plots, but there was no significant difference in length of damage. Microhabitat significantly affected the number of consecutive hours per day that were 35°C or above (critical temperature for preimaginal *T. exiguum* survival). Soil surface with no cover had the greatest number of hours 35°C or greater, followed by soil surface with herbaceous cover, and canopies of small trees (0.4 m tall). Canopy habitats in larger trees (0.9 – 1.8 m tall) had the most moderate temperature conditions. Parasitoid emergence was significantly reduced in response to increasing number of consecutive hours 35°C or greater. Predation of *T. exiguum* prior to emergence, though relatively minor, was significantly affected by microhabitat and by the length of time capsules were in the field before emergence (i.e. cohort number). The reduction of *R. frustrana* populations by mass-release of *Trichogramma* is technically feasible. In order to make these releases practical, however, we suggest several considerations for future research. Large scale *Trichogramma* releases could be studied to evaluate possible area-wide effects and residual effects over multiple tip moth generations. Combining several releases of *Trichogramma* into a single application may be accomplished by a single release of multiple cohorts timed to emerge over a 7–8 day period. The efficacy of such an approach should be studied. Consideration might be made of plantation management practices that result in adequate vegetational cover for survival of encapsulated *Trichogramma* broadcast on the soil surface, but do not interfere with tree growth. Though unlikely with a native parasitoid, the potential for non-target impacts should be considered in any future evaluations.

INTRODUCTION

The purpose of this paper is to examine the potential for using biological control as a practical pest management tool for *R. frustrana* in southeastern pine plantations. We briefly review the literature on naturally occurring parasitoids and predators of *R. frustrana*, and the use of one parasitoid group, *Trichogramma*, in pest management. We also summarize data from a study demonstrating the efficacy of *Trichogramma* releases and the suitability of microclimate in pine plantations for *Trichogramma* survival. Finally, we include a discussion of the research questions that should be addressed in determining the potential for *Trichogramma* releases to suppress *R. frustrana* in commercial pine plantations.

Biological Control and *R. frustrana*

There are three general approaches to implementing biological control in pest management systems. The first, importation (or classical) biological control involves importing effective natural enemies of exotic pests from the pests' homeland. However, *R. frustrana* is a native pest, so the classical approach does not apply to it. The so-called "neo-classical" approach, in which natural enemies that attack related pests in other geographic locations are sought (Hokkanen and Pimentel 1989), might be considered. However, the neoclassical approach is considered ecologically risky and is frowned upon by some in the conservation community (Simberloff and Stiling 1996).

[1] Orr, Assistant Professor, and Philip, Graduate Student, Department of Entomology, College of Agriculture and Life Sciences, North Carolina State University, Raleigh, NC, 27695-7613; Suh, Research Entomologist, USDA ARS APMRU, 2771 F & B Road, College Station, TX 77845; McCravy, Department of Entomology, University of Georgia, Athens, Georgia 30602-2603, and DeBarr, Research Entomologist (retired), USDA Forest Service, Southern Research Station, Forestry Sciences Laboratory, Athens, Georgia 30602.

Citation for proceedings: Berisford, C. Wayne; Grosman, Donald M., eds. 2002. The Nantucket pine tip moth: old problems, new research. Proceedings of an informal conference, the Entomological Society of America, annual meeting. 1999 December 12–16. Gen. Tech. Rep. SRS–51. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 68 p.

Conservation biological control involves remediation of factors in systems that limit the effectiveness of natural enemies. This can involve activities as diverse as modifying pesticide use practices or the creation of additional habitat for natural enemies. The potential for conservation biological control of *R. frustrana* through pesticide use modification appears low because of the limited range of insecticide products available and the narrow and sometimes unpredictable timing window for their application (Fettig and Berisford 1999, McCravy 1998). In addition, resident populations of natural enemies do not adequately suppress *R. frustrana* populations on their own (McCravy 1998). The use of habitat manipulation to increase natural enemy effectiveness may also be difficult. The intensive site preparation and early chemical weed control employed to increase survival and growth rate of seedling pines has apparently resulted in higher tip moth densities. The levels of associated vegetation in pine plantations has been shown to be a factor that predisposes stands to tip moth damage (Warren 1963, Berisford and Kulman 1967, Ross and others 1990). Berisford (1988) suggested that this relationship might be due to variation in the availability of alternate hosts or pollen and nectar sources for natural enemies. However, McCravy (1998) demonstrated no relationship between parasitism levels of *R. frustrana* and vegetational diversity.

Augmentation biological control involves augmenting populations of natural enemies not present in high enough numbers to be effective, by means of releasing lab reared enemies. This approach has been evaluated by Orr and others (2000), and has been shown to be technically feasible for *R. frustrana* suppression in a study presented below.

Natural Enemies of *R. frustrana* in Pine Plantations

The concealed nature of *R. frustrana* (i.e. small larvae mine in needles and larger larvae tunnel into shoots) means that larvae may not be as susceptible to predation, possibly reducing the role predators play in natural regulation of tip moth populations. However, there is a rich complex of over 60 parasitoid species that attack *R. frustrana* eggs, larvae, and pupae (Frank and Foltz 1997). Some of the parasitoids attacking *R. frustrana* may be important in regulating populations of this pest (Berisford 1988).

Natural populations of *Trichogramma* spp. wasps are responsible for most *Rhyacionia frustrana* egg mortality. Garguillo and Berisford (1983) found parasitism of *R. frustrana* eggs by *Trichogramma* to be as high as 47 percent. Similarly, Yates (1966) found 64.5 percent egg mortality due to *T. minutum* Riley in central Georgia. McCravy and Berisford (1998) reported 37.2 percent and 43.3 percent parasitism of spring and summer generation eggs, respectively. The species responsible for this parasitism were identified as primarily *T. pretiosum* Riley and *T. exiguum* Pinto & Platner, with a small number of eggs attacked by *T. marthae* Goodpasture (McCravy 1998).

McCravy (1998) found overall pine tip moth larval and pupal parasitism to be 44.8 percent on the Georgia coastal plain, and Freeman and Berisford (1979) found 42 percent parasitism on the Georgia piedmont. Eikenbary and Fox (1965) reported tip moth parasitism to 41 percent and 26 percent on the South Carolina coastal plain and piedmont, respectively. The species primarily responsible for tip moth parasitism are the tachinid fly *Lixophaga mediocris* Aldrich, the ichneumonid wasp *Campoplex frustranae* Cushman, the eurytomid wasp *Eurytome pini* Bugbee, and the eulophid wasp *Hyssopus rhyacioniae* Gahan (McCravy 1998).

As indicated above, one possible approach to biological control of *R. frustrana* in pine plantations is the augmentation of natural enemies. Garguillo and Berisford (1983) found that biotic mortality factors affecting *R. frustrana* are most important in the egg and pupal stages. Since pupal mortality occurs after the trees are already damaged, it seems logical to focus on the egg stage as a target and *Trichogramma* wasps as a natural enemy for augmentation.

Use of *Trichogramma* in Augmentation Biological Control

Parasitic wasps in the genus *Trichogramma* are the most commonly employed arthropod in augmentation biological control programs. These parasitoids have several advantages as biological control agents, including relative ease of rearing and the fact that they kill their host in the egg stage before it causes feeding injury (Wajnberg and Hassan 1994). *Trichogramma* releases are currently used to treat an estimated 32 million hectares annually for control of agricultural and forest pests (Li 1994), and are being studied in over 50 countries worldwide (Smith 1996). Of the approximately 180 species of *Trichogramma* known, over 70 have been employed as biocontrol agents, and 20 are commonly mass reared and released in augmentation programs (Li 1994, Pinto 1998). Individuals to be mass reared are usually collected near the planned release site to ensure that the *Trichogramma* are adapted to that area (Smith 1996).

Trichogramma are exclusively egg parasitoids seldom exceeding 0.7 mm in length (Pinto 1998). They have been recorded from hosts in seven insect orders, but are predominantly parasitoids of lepidoptera (Pinto and Stouthamer 1994). *Trichogramma* have a worldwide distribution and comprise the largest genus within the family Trichogrammatidae (Pinto 1998).

Augmentation biocontrol with *Trichogramma* can take the form of inundative or inoculative releases (Li 1994). Inundative releases require the mass rearing and release of many individuals to combat an existing pest problem. Inoculative releases involve fewer individuals released early in the cropping season to prevent pests from reaching damaging levels. Many *Trichogramma* release programs are actually a hybrid of these two release approaches. Parasitoids are released inundatively only at the beginning of the oviposition period of the targeted pest with the expectation that their progeny will continue to provide pest suppression through the remainder of the oviposition period. Reducing the number of releases required for a single generation of a pest makes this hybrid approach more economical.

FEASIBILITY OF *TRICHOGRAMMA* RELEASES FOR *R. FRUSTRANA* SUPPRESSION.

A study conducted in North Carolina in 1998 evaluated the feasibility of using inundative releases of *T. exiguum* for suppression of second generation *R. frustrana* in loblolly pine, *P. taeda* L., plantations. This was the first study to consider the augmentation of natural enemy populations for *R. frustrana* control.

Study Design and Plot Management

The experiment was set up using a complete block design, with three field locations (each with a treatment and a control plot) acting as three blocks. Two field locations were near Connarista, North Carolina, and a third was near Aulander, in Bertie County, North Carolina. The treatment was *T. exiguum* release; controls were not treated with *T. exiguum*, and insecticides were not used on any of the plots. Within each location, the *Trichogramma* release plot was at least 400 m downwind (based on prevailing wind direction for that area) from the control plot to reduce possibility of parasitoid dispersal into control plots. Plots were approximately 0.4 ha each.

Pinus taeda seedlings (1 – 0) were planted in rows spaced 3.5 m apart from furrow to furrow, and 1.7 m apart within rows. Field locations 1 and 2 were planted on 23–27 January, 1997, and field location 3 on 31 Jan – 1 Feb, 1997. All three locations received the following herbicide treatment per ha: May, 97, 946 ml Velpar L® (hexazinone) and 89 ml Oust® (sulfoneturon) (banded on rows); June, 97, 118 ml Arsenal® (imazapyr) (broadcast), 0.74 kg Velpar DF® and 89 ml Oust® (broadcast).

Data Analysis

Tip moth egg, larval, and pupal counts were transformed by taking the square root prior to analysis. These data and damage data were analyzed using analysis of variance (PROC GLM, SAS Institute, Cary, NC, USA, 1996). Hatch and parasitism data were subjected to logistic regression analysis (PROC GENMOD with PSCALE option and likelihood ratio tests, SAS Institute, Cary, NC, USA, 1996). Temperature, parasitoid emergence, and predation data were analyzed using analysis of variance (PROC GLM, SAS Institute, Cary, NC, USA, 1996). Parasitoid emergence data were subjected to arcsine square root transformation prior to analysis. The influence of temperature on *T. exiguum* emergence was examined with a correlation analysis (PROC CORR, SAS Institute, Cary, NC, USA, 1996).

R. frustrana Population Sampling

At each of the three field locations, *R. frustrana* egg density was estimated in release and control plots by clipping the upper 22–25 cm section of 20 sub-terminal shoots (1 shoot per tree) randomly selected from the central 50 percent of the plot. Shoot samples were placed in Zip-loc® bags and immediately taken to a laboratory where they were examined for *R. frustrana* eggs. Total number of parasitized and viable eggs were recorded for each plot. Shoots were collected and examined every 3–4 d beginning 29 May.

Second generation *R. frustrana* eggs were first detected between 29 May and 1 June at all three field locations (data for all release plots combined presented in fig. 1). At field site 1, at peak oviposition *R. frustrana* egg density in both *T. exiguum*-treated and control plots was 2.2 eggs per shoot, with both peaks occurring on 8 June. At field site 2, peak oviposition in the *T. exiguum*-treated plot was 1.7 eggs per shoot (5 June) and 2.3 eggs per shoot (8 June) in the control plot. At field site 3, peak oviposition in the *T. exiguum*-treated plot was 1.0 eggs per shoot (8 June) and 0.8 eggs per shoot (8 June) in the control plot. Overall, there was no significant difference in egg numbers ($df=1,14$, $F=0.64$, $P>0.05$) between *T. exiguum*-treated and control plots, therefore data from the three fields sites were combined.

Source, Release Rates, and Quality of *Trichogramma*

Proper selection of species, biotypes or ecotypes has been shown to be crucial for successful *Trichogramma* augmentation (Kot 1979; Voronin and Grinberg 1981; Pak 1988). McCravy and Berisford (1998) reported that two species responsible for *R. frustrana* parasitism were *T. pretiosum* and *T. exiguum*. We selected *T. exiguum* because prior experience had indicated this was a vigorous species that retained very high quality under long-term mass rearing (Suh and others 1998). To ensure we had a strain that was well adapted to the area of intended release, we collected material for our culture from a site near Plymouth, North Carolina, within 50 km of release sites.

Trichogramma exiguum were reared from parasitized sentinel corn earworm, *Helicoverpa zea* Boddie (Lepidoptera: Noctuidae) eggs placed in woodlots adjacent to agricultural fields near Plymouth, North Carolina. Eight isolines (colonies begun from a single mated female) were collected and species identity confirmed by John Pinto, University of California at Riverside. Parasitoids were shipped to BIOTOP (Valbonne, France) where isolines were combined, mass reared, and formulated for field release. The formulation consisted of waxed cardboard capsules (approx. 5 cm^3) each containing an average of 1319 ± 140 *T. exiguum* developing inside Mediterranean flour moth, *Ephestia kuehniella* Zeller, eggs. Four small holes made during the encapsulation process were just large enough for adults to escape but small enough to prevent most predators from entering the capsules.

Shipments from BIOTOP to NCSU were made weekly, via commercial air freight. Each of three weekly shipments (beginning 25 May) consisted of three cohorts of parasitoids whose development was staggered approximately 25 Celsius degree days apart. For each shipment, a HOBO XT® Temperature Logger (Onset Computer Corp., 536 MacArthur Blvd., Box 3450, Pocasset, MA 02559-3450), programmed to record temperature hourly was placed alongside capsules to monitor temperature fluctuations. These temperature data allowed estimation of degree day accumulation during shipping and handling so accurate predictions of adult emergence could be made.

Three releases (R1 - R3), spaced 7 d apart, were made in each release plot beginning 29 May (fig. 1). Each release contained three cohorts of capsules differing in *T. exiguum* development. One set of capsules contained *T. exiguum* expected to emerge within 12–24 h, the second within 60–

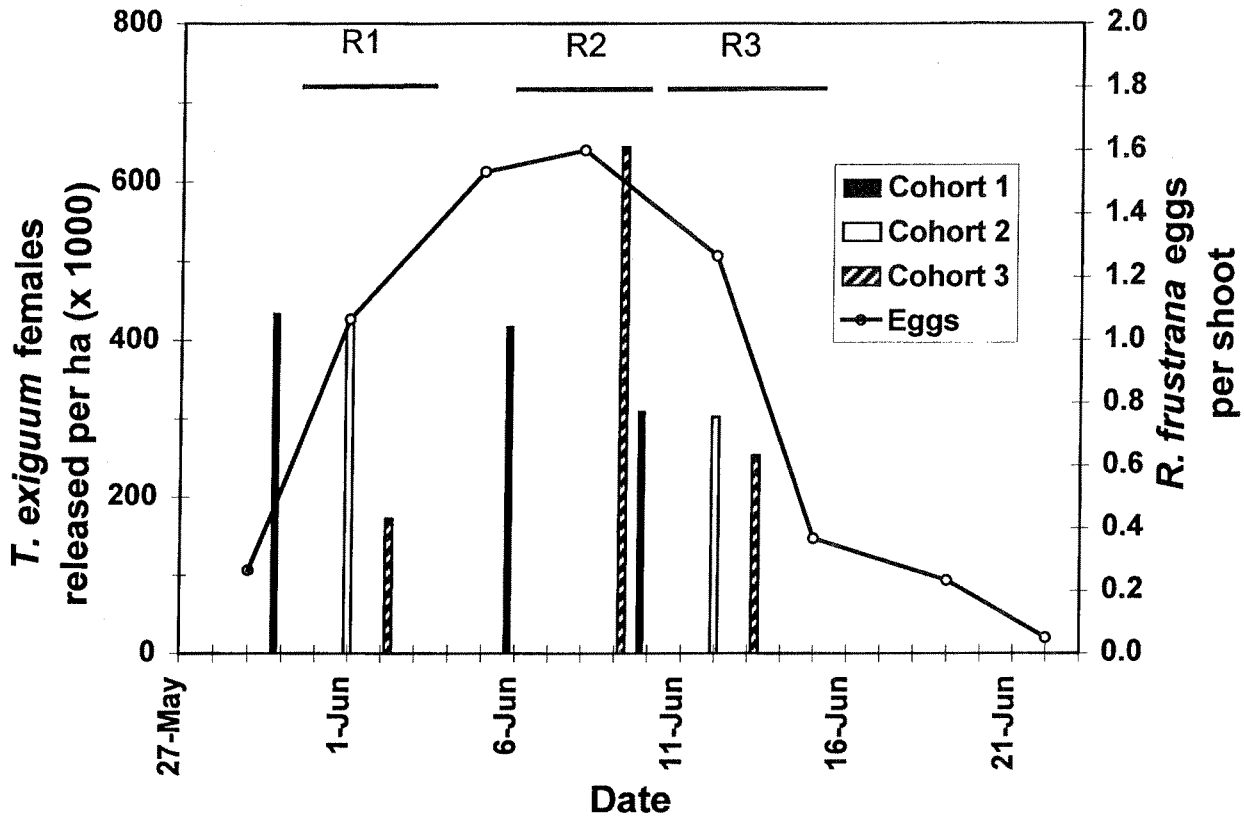

Figure 1—Mean *Rhyacionia frustrana* eggs per shoot and mean number of *Trichogramma exiguum* released with date of peak emergence for each cohort (three releases R1 – R3, three cohorts each). Data presented are from all release plots combined. Bertie County, NC, USA, 1998.

72 h, and the third within 96–108 h after field release. *Trichogramma* capsules were hand-placed at 100 release points evenly spaced throughout each release plot. Each release point had a pair of waxed cone-shaped paper cups, located 0.3 to 0.5 m above the soil surface in the tree canopy, into which capsules were placed. Cups were spaced approx. 5.5 m apart within rows and 7 m apart across rows. *T. exiguum* were released at a rate of 328,238 ± 88,379 females/ha/ cohort/release (determined from data presented below and in fig. 1).

Stringent quality control protocols were followed once material arrived in North Carolina to ensure that only high quality *T. exiguum* were utilized in this study. Poor quality of released natural enemies can lead to unsatisfactory pest suppression and unpredictable results (Hoy and others 1991).

Samples of five capsules per *T. exiguum* cohort were frozen immediately upon receipt to determine production emergence (i.e. percentage of parasitized eggs added to fresh eggs during production). Emergence percentages from all subsequent samples were estimated by counting emergence holes in 50 black (parasitized) eggs/capsule, and subtracting production emergence. *Trichogramma exiguum* adults from a second sample of 10 capsules per cohort were allowed to emerge over a seven day period at 25° C, 80 percent RH, and a 16L:8D photoperiod after which capsules were frozen. For each of the 10 individual capsules, emergence was estimated, 30 adults were randomly selected to estimate sex ratio, and 10 females were randomly selected to estimate percent brachyptery. A third sample of 5 capsules per cohort was used to estimate female longevity according to procedures described by Cerutti and Bigler (1991).

To estimate field release rates, a fourth sample of 10 capsules per cohort was taken just prior to each release, and the total number of parasitized (blackened) eggs per capsule was counted. To assess field emergence (i.e. timing of releases), a fifth sample of 25 capsules per cohort was hand-placed in waxed cone-shaped paper cups located 0.5 m above the soil surface in the tree canopy, adjacent to a release plot. Five capsules from each cohort were collected on the day of release (day 0), 3, 5, 7, 10, and 11 d after each release, and frozen until they could be sampled.

Mean (± SD) *T. exiguum* emergence under laboratory conditions for released cohorts was 96 ± 2 percent, consisting of 74 ± 3 percent females, of which 1 ± 1 percent displayed brachyptery. Female longevity for released cohorts averaged 18 ± 3 d. In comparison, the mean life span of adult female *T. exiguum* reported in other laboratory studies ranged from 4.1 to 8.6 d (Harrison and others 1985, Ram

and Irulandi 1989). Mean emergence of parasitoids under field conditions was 96 ± 4 percent. A release rate of 328,238 ± 88,379 females/ha/cohort/release was estimated after taking into account the number of parasitized *E. kuehniella* eggs per capsule, percent of females emerging from capsules, removal of brachypterous females, and emergence of parasitoids under field conditions (fig. 1). Peak emergence of parasitoid cohorts from the three releases occurred every 1 to 4 days throughout the peak oviposition period of *R. frustrana* (fig. 1).

Parasitism of *R. frustrana* Eggs

The level of egg parasitism in *T. exiguum* release and check plots was measured on 1, 5, 8, 12, and 15 June. For each date, *R. frustrana* eggs were collected from shoots used to estimate egg densities. To standardize parasitism data, only light orange-colored eggs (2–3 d-old) were clipped from shoots and used to determine percent parasitism. Clipped eggs (10–35 eggs per plot) were placed on premoistened filter paper (Qualitative P5, 5.5 cm diam.) within petri dishes (6 cm diam.) and held at 25°C, 80 percent humidity, and a 16L:8D photoperiod for 7–8 d at which time eggs were classified as either hatched, black-head stage, non-viable, or parasitized. A percentage was calculated for each category.

Parasitism of *R. frustrana* eggs collected throughout the study period was significantly increased by 29 percent ($F_{1,10}$=8.30, P=0.016) and egg hatch was significantly reduced by 47 percent ($F_{1,8}$=62.0, P<0.001) in *T. exiguum*-treated plots (combined) compared with control plots (combined) (table 1). The species responsible for parasitism in *T. exiguum*-release plots were *T. exiguum* (100 percent of parasitized eggs collected), and in control plots *T. exiguum* (92.4 percent), *T. marthae* (3.8 percent), *T. pretiosum* (1.9 percent), and *T. minutum* (1.9 percent). Parasitism in control plots was approximately 42 percent (table 1) which seems relatively high, but is in line with the 43.3 percent parasitism of summer generation *R. frustrana* eggs by resident populations of *T. exiguum, T. pretiosum, and T. marthae* in Georgia pine plantations reported by (McCravy and Berisford 1998).

Larval infestation

During shoot examinations for eggs, numbers of instar 1–2, 3–4, 5 larvae (determined by head capsule size; see Fox and others 1972), and pupae found in shoots and needles were recorded for each release and control plot. The number of larvae in instar categories 1–2, 3–4, and 5 per shoot was significantly lower in *T. exiguum*-treated plots compared to control plots (df=1,14, F=51.41, P=0.0001; df=1,14, F=16.79, P=0.0004; df=1,14, F=26.02, P=0.0001), with a mean (± SD) reduction in *T. exiguum*-treated plots of 65 ± 8 percent, 63 ± 10 percent, and 57 ± 4 percent, respectively (fig. 2). The number of pupae per shoot was also significantly (df=1,14, F=6.91, P=0.02) reduced by 62 ± 30 percent in treated plots.

Population levels of *R. frustrana* were high in all plots used in this study (see fig. 2), presenting a challenging environment in which to test augmentation of natural enemies for suppression of this pest. The percentage decrease in egg survival, and the percentage reduction in neonate and fifth instar larval numbers all had approximately the same absolute value (47 percent, 65 percent and 57 percent, respectively). This suggests there was no compensatory mortality in the larval stage during this study. This is an important consideration since compensatory mortality in larval stages followed *Trichogramma* releases in rice (Van Hamburg and Hassell 1984) and cotton (Suh and others 1998). Andow and others (1995) found a direct relationship between egg mortality and larval mortality in corn. Although there are few studies addressing this concern, the variability in results suggests that the issue of compensatory mortality should be addressed in each system in which *Trichogramma* populations are to be augmented.

Damage to trees

The number of mined needles and percentage of shoots damaged was also recorded while shoots were examined for eggs. A final shoot damage assessment was made on 20 July in each release and control plot. For each plot, 50 trees were randomly selected from the central 50 percent of the plot. Each tree was divided into three sections (terminal shoot; top whorl shoots; and remaining tree shoots), all shoots were sampled, and the length of damage in shoots within the first two sections measured with a ruler.

Despite significant reductions in larval numbers, no significant difference in percentages of terminal damage

Table 1—Mean ± SD percent parasitism and egg hatch of second generation *Rhyacionia frustrana* eggs collected from *T. exiguum*-treated and control plots in *Pinus taeda* plantations, June 1–15, 1998 in Bertie County, NC

		Percentage of *R. frustrana* eggs which were:		
Plot type	n	Parasitized	Hatched	Non-viable
T. exiguum release	287	53.7 ± 12.2 a	22 ± 4 b	24 ± 10 a
Control	241	41.6 ± 20.8 b	41 ± 6 a	17 ± 13 a

Values within a column followed by different letters are significantly different (logistic regression, P≤ 0.05).

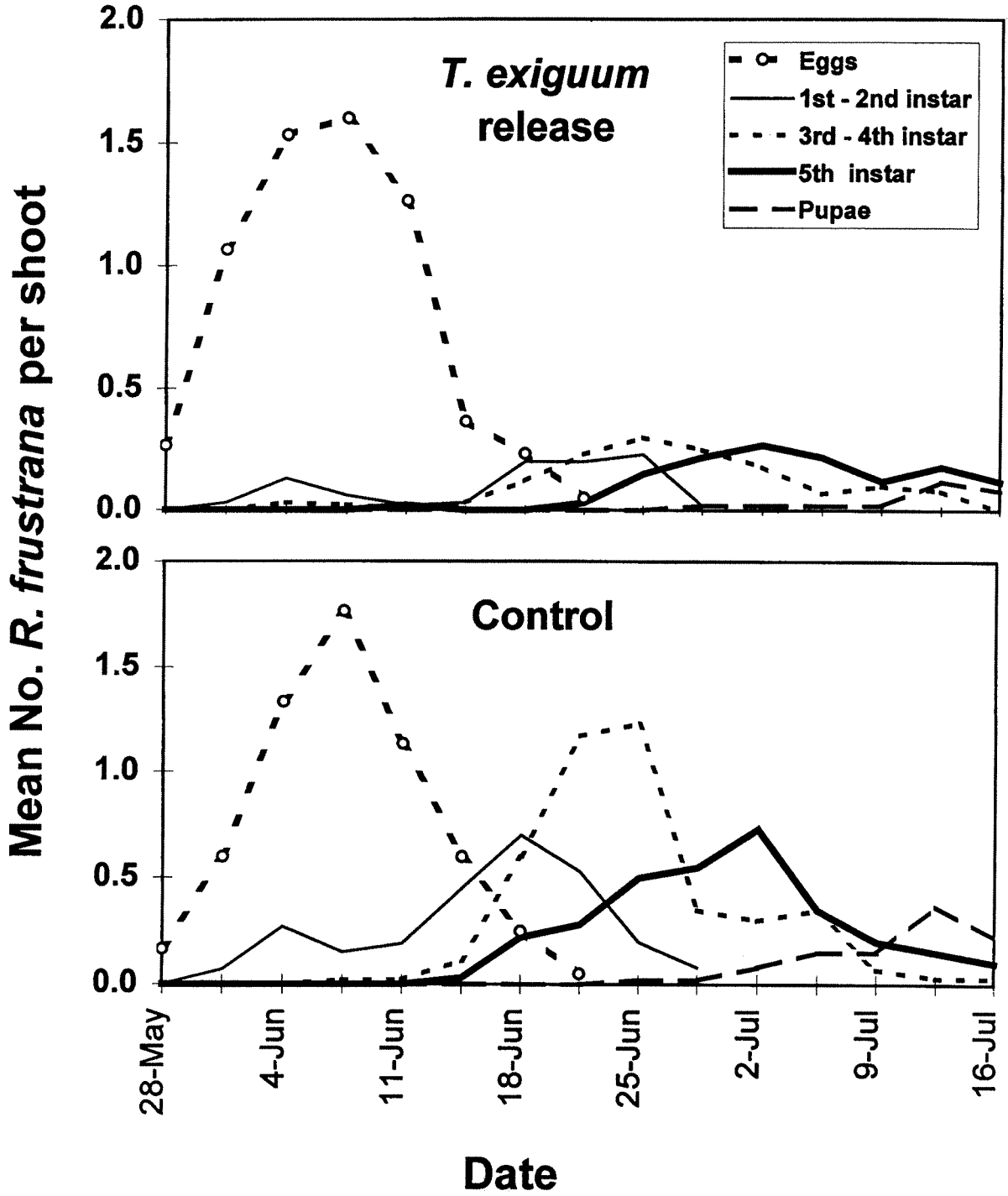

Figure 2—Mean number of *Rhyacionia frustrana* eggs, larvae, and pupae per shoot in *Trichogramma exiguum* release plots and control plots. Bertie County, NC, USA, 1998.

(df=1,2, F=1.28, P=0.376) was found (table 2). However, there was a significant difference in the length of tunneling damage within terminals (df=1,2, F=5.69, P=0.019). No significant difference was found between release and control plots in the number of top whorl shoots (df=1,2, F=1.04, P=0.416), but there was a significant difference in number of top whorl shoots that were attacked (df=1,2, F=28.36, P=0.034). However, there were no significant differences in the length of tunneling within top whorl shoots (df=1,2, F=1.70, P=0.322). There were no significant differences between release and control plots in the number of shoots below the top whorl (df=1,2, F=0.28, P=0.651), but the

Table 2—Mean ± SD percent of *Pinus taeda* shoots attacked by second generation *Rhyacionia frustrana* and length of tunneling in shoots occurring on different parts of trees[a] at three field sites. Bertie Co., NC, USA, 1998

	Shoots attacked on			Length of tunneling	
Treatment	Terminal	Top whorl	Remainder of tree	Terminal	Top whorl
	Percent			*Cm*	
T. exiguum release	31 ± 16	30 ± 4 a	33 ± 4 a	2.3 ± 1.3 a	1.8 ± 0.3 a
Control	45 ± 10 a	49 ± 7 b	53 ± 3 b	3.5 ± 2.5 b	2.1 ± 0.2 a

Values within a column followed by different letters are significantly different (ANOVA, P <0.05)
[a] Fifty trees were sampled in each plot; data presented are averaged from 150 trees each for the *T. exiguum* release and control plots.

number of these shoots that were attacked was significantly lower in *T. exiguum* plots (df=1,2, F=5.48, P=0.144) (table 2).

Microclimatic effects on *T. exiguum*

In addition to assessing efficacy of *T. exiguum* releases, we also assessed *T. exiguum* application methodology by monitoring temperature, *T. exiguum* emergence, and predation of *T. exiguum* in six distinct microhabitats found within first and second year pine plantations. One-year-old trees used for this study were in field location 1 used in the release study. The two-year-old trees were located adjacent to field location 1, and were planted 1 March, 1996 on the same spacing described in the release study. The stand received the following herbicide treatments: April 96, banded 946 ml Velpar L® and 89 ml Oust®; June 96, broadcast 118 ml Arsenal®; April 97, broadcast 946 ml Velpar L® and 89 ml Oust®; June 97, broadcast 118 ml Arsenal®.

The microhabitats studied were: 1) soil surface with no cover in 1st year plantation; 2); soil surface with herbaceous cover in 1st year plantation 3) canopy (mid-height) of small (0.46 m) 1st year plantation trees; 4) canopy (mid-height) of tall (0.92 m) 1st year plantation trees; 5) canopy (mid-height) of 2nd year plantation trees; 6) soil surface with herbaceous cover in 2nd year plantation. Temperature was monitored in each habitat with a datalogger (Model CR10, Campbell Scientific, Inc., 815 W. 1800N, Logan, Utah 84321-1784) with 24 temperature probes (Model 107 on 100 ft. wire leads) set up in between the stands of 1- and 2-yr-old *P. taeda*. Each temperature probe was completely enclosed within a sheath, constructed from the cardboard used to encapsulate *Trichogramma,* in order to simulate conditions inside capsules. Probes were placed in the six microhabitats, replicated four times (total of 24 sites). The datalogger was programmed to take one measurement every minute and record the average on an hourly basis for each temperature probe. Measurements were begun 29 May, and continued through 19 June. The critical temperature at which *T. exiguum* survival is reduced is 35°C (Harrison and others 1985). We therefore calculated the number of consecutive hours each day that were at or above this temperature.

To assess the effect of microclimate on *T. exiguum* emergence in the different microhabitats, two capsules from each cohort for two releases (1st and 3rd) were placed in white nylon mesh bags alongside probes. In the canopy, capsules were placed in cone-shaped waxed paper cups used for the release study. One cohort was programmed to emerge within 12–24 h, the second within 60–72 h, and the third within 96–108 h after field release. Capsules from cohorts 1 – 3 were collected 7, 10 and 14 d, respectively, following field release and then were immediately frozen. The emergence percentage for each capsule was determined using procedures described in the quality control section. The first set of capsules was placed in the field on 29 May, and the second set on 12 June.

Microhabitat had a significant influence on the number of consecutive hours per day that were 35°C or above ($F_{5,18}$= 3.34, P = 0.025) (table 3). This value varied significantly between the two releases for which microclimate data were collected ($F_{1,18}$= 9.56, P = 0.006), therefore subsequent analyses were conducted on the two releases separately (table 3). During the first release period (May 29 – June 5) the bare soil surface had the greatest number of hours 35°C or greater, followed by the two soil surface microhabitats with herbaceous cover and the 0.4 m tree canopies. The two canopy habitats in the largest trees had the most moderate temperature conditions. During the second release period (June 12 – 19) temperature conditions were more moderate due to cloudy weather and the soil surface with no cover had significantly greater number of hours 35°C or greater when compared to all other microhabitats.

Parasitoid emergence (all microhabitats combined) was significantly reduced in response to increasing number of consecutive hours 35°C or above (Pearson's Correlation Coefficient = -0.673, P = 0.0001) in the first release period, but was not significantly reduced in the second period (Pearson's Correlation Coefficient = -0.191, P = 0.23) (table 3).

Table 3—Mean ± SD microhabitat temperatures, and emergence and predation of encapsulated *Trichogramma exiguum* exposed to various microhabitats within *Pinus taeda* plantations. Bertie County, NC, USA, 1998

Exposure period	Microhabitat description	Successive hrs (± SD) above lethal temperature (35° C) per day	T. exiguu emergence	Predation of T. exiguum
			---------- *Percent* ----------	
May 29–	1st yr. trees, soil surface, no cover	5.2 ± 3.0 c	47.8 ± 37.3 a	0.0 ± 0.0 a
June 5	1st yr. trees, soil surface, herbaceous cover	1.5 ± 2.4 b	68.3 ± 31.5 ab	16.7 ± 32.6 a
	1st yr. 0.4 m trees, canopy	0.9 ± 1.0 b	90.5 ± 11.3 b	25.0 ± 33.7 ab
	1st yr. 0.9 m trees, canopy	0.3 ± 0.3 a	95.0 ± 6.9 b	8.3 ± 19.5 a
	2nd yr. 1.8 m trees, soil surface, herbaceous cover	1.6 ± 2.5 b	98.2 ± 2.5[a]	55.0 ± 49.7 b
	2nd yr. 1.8 m trees, canopy	0.4± 0.6 a	94.2 ± 6.7 b	4.2 ± 14.4 a
June 12–19	1st yr. trees, soil surface, no cover	3.9 ± 2.5 b	82.6 ± 31.5 a	8.3 ± 19.5 a
	1st yr. trees, soil surface, herbaceous cover	1.0 ± 1.9 a	91.8 ± 9.1 a	16.7 ± 24.6 a
	1st yr. 0.4 m trees, canopy	0.4 ± 0.6 a	90.7 ± 12.8 a	16.7 ± 32.6 a
	1st yr. 0.9 m trees, canopy	0.1 ± 0.2 a	89.9 ± 11.5 a	4.2 ± 14.4 a
	2nd yr. 1.8 m trees, soil surface, herbaceous cover	0.8 ± 1.0 a	78.6 ± 28.9[a]	58.3 ± 46.9 b
	2nd yr. 1.8 m trees, canopy	0.1 ± 0.2 a	97.2 ± 4.5 a	22.7 ± 34.4 ab

Within a given date, values within a column followed by different letters are significantly different (LS Means, P ≤0.05).
[a] Heavy predation resulted in too many missing data points for PROC GLM to estimate a comparative value.

Predation of *T. exiguum* capsules

Predation of parasitized *E. kuehniella* eggs within capsules was also noted while emergence data were being recorded. Predation was either very heavy (< 100 eggs remaining in a capsule) or not present. When both capsules of a pair had heavy predation, we recorded 100 percent predation for the pair; if only one capsule had heavy predation, 50 percent was recorded; if neither capsule had obvious predation, 0 percent was recorded. Ants collected from inside capsules were identified to genus by David Stephan, Dept. of Entomology, North Carolina State University, USA.

Predation by ants in the genus *Crematogaster* was significantly affected by microhabitat ($F_{5,18}$= 3.30, P = 0.027); the soil surface in second year plantations with herbaceous ground cover had significantly more predation than the other microhabitats (LS Means, P £ 0.05) (table 3). The length of time capsules were in the field before *T. exiguum* emergence (i.e. cohort number) also significantly affected predation ($F_{2,69}$= 16.3, P < 0.001), but not emergence ($F_{2,58}$= 2.71, P = 0.075). Capsules in the third cohort that had been in the field 6 d prior to parasitoid emergence had significantly higher predation than those exposed for 2 or 4 d (LS Means, P £ 0.05) (table 4).

Predation in this study reduced the number of *Trichogramma* available for emergence in field plots, thereby reducing the actual numbers of wasps/ha considerably below those originally planned. Ants of the genus *Crematogaster* appeared to be responsible for this predation, since they were the only potential predators found inside capsules from which predation was noted. The ants apparently gained entry to the capsules by chewing the perimeter of and widening the holes that are punched in capsules during production to allow *Trichogramma* escape in the field. Although the potential impediment of predation has been noted in other *Trichogramma* release projects (Smith 1996), none utilized encapsulated material as in this study. Significant predation was not observed in cotton or apples following release of encapsulated *T. exiguum* (Suh and others 1998, Shetty 2000), nor in corn when encapsulated *T. brassicae* were released (Kabiri and others 1990, Orr 1993).

SUMMARY OF FEASIBILITY STUDY

Larval *R. frustrana* populations were reduced considerably by *T. exiguum* in this study. However, the percentage infestation of top whorl shoots was not as greatly reduced. This reflects the fact that there were multiple larvae in infested shoots in control plots, and therefore a reduction in larval numbers did not necessarily lead to a proportional reduction in number of infested shoots. There was, however, a significant reduction in the length of damage within shoots. This, plus the apparent lack of compensatory mortality, indicates that *Trichogramma* release for suppression of *R. frustrana* populations is technically feasible. Additional studies will be required to evaluate the potential of this technology to be used on an operational basis. Some possible considerations for these studies are presented below.

Table 4—Mean ± SD emergence and predation of *Trichogramma exiguum* following varying periods of exposure to field conditions within *Pinus taeda* plantations. Bertie Co., NC, USA, 1998

Exposure period	No. days *T. exiguum* exposed to field conditions prior to emergence	*T. exiguum* emergence	Predation of *T. exiguum*
		---------- *Percent* ----------	
May 29–June 5	2	86.4 ± 24.5 a	10.4 ± 25.4 a
	4	79.1 ± 26.8 a	4.4 ± 20.9 a
	6	75.0 ± 34.2 a	37.0 ± 40.5 b
June 12–19	2	89.6 ± 21.4 a	13.0 ± 31.0 a
	4	92.5 ± 15.7 a	22.9 ± 36.1 ab
	6	85.1 ± 18.1 a	27.1 ± 36.1 b

Within a given date, values within a column followed by different letters are significantly different (LS Means, $P \leq 0.05$).

FUTURE RESEARCH CONSIDERATIONS.

There are a variety of questions that should be addressed before an operational *Trichogramma* release system could be implemented. For example, release plots in this study were each 0.4 ha, and were surrounded by large untreated portions of the study plantations. Releasing *Trichogramma* on a much larger scale, for example on an entire plantation, would allow an evaluation of whether *R. frustrana* suppression can be improved by area-wide treatment effects over multiple generations. Such area-wide effects have been demonstrated for other biologically-based pest management tactics such as mating disruption with semiochemicals (Niwa and others 1988, Cardé and Minks 1995).

An examination of temperatures and *T. exiguum* emergence within various microhabitats of pine plantations in the feasibility study revealed significant differences in survival of *T. exiguum* in the different microhabitats. The canopy of both first and second year trees was the most suitable microclimate for *T. exiguum* emergence. However, distributing capsules into tree canopies would not be a practical way to release *Trichogramma* in large pine plantations. Likely, the most acceptable means of distribution would be broadcast application by helicopter. Capsules distributed in this manner would probably end up on the soil surface. Where the soil surface was bare in our study, *Trichogramma* capsules distributed on the soil surface faced considerable reductions in emergence. We also found that the longer capsules remained in the field prior to adult emergence, the lower the emergence. This could be especially important since in order to make *Trichogramma* releases practical, only one application (containing several cohorts that would emerge over a 7–8 d period) could be made per *R. frustrana* generation. Future considerations for optimizing the success of *Trichogramma* release methodology in pine plantations should include a consideration of the possible selection of high temperature tolerant strains, and an examination of various types of vegetational management on microhabitat and *Trichogramma* emergence.

To date, a relationship between vegetational diversity in pine plantations and natural enemy activity has not been demonstrated (McCravy 1998). However, egg parasitoid longevity and parasitism of target pests can be substantially increased by the presence of nectar-bearing plants and/or honeydew in some agroecosystems (Orr 1988). In the current study we found that ground cover and its effect on microclimate significantly influenced emergence of released parasitoids. Consideration of pine plantation management practices, their effect on ground cover, and the subsequent impact on *Trichogramma* releases may lead to improved *Trichogramma* performance, and overall control of *R. frustrana*.

The predation of *T. exiguum* by ants in our study may have been due to the high numbers of capsules clustered in cups or on the ground as part of our experimental design. Encapsulated *Trichogramma* are usually broadcast, so that they would have a uniform rather than clumped distribution. It would be of value to assess broadcast application of capsules on the ground versus clumped distribution (as in this study) as a method of reducing predation.

Another consideration that should be made prior to commercial implementation is the potential for *Trichogramma* releases to have non-target impacts. Historically, biological control has enjoyed a reputation as an environmentally safe alternative to chemical. Recently, however, concern has been raised regarding potential non-target impacts of biocontrol practices (Follett and Duan 1999). Although the focus of most attention is on the introduction of non-native organisms in classical biocontrol programs, the augmentation of native natural enemies may also a concern (Orr and others 1999).

Because non-target impacts are of greatest concern outside the release area, dispersal ability of *Trichogramma* is a key component of potential non-target impacts. Studies on dispersal of *Trichogramma* have demonstrated contradicting results. Most studies indicate that *Trichogramma* dispersal is limited (Bigler and others 1989, McDougall and Mills 1997).

However, Stern and others (1965) demonstrated that individuals could travel up to 1100 m from the release site. Bigler and others (1990) found that levels of parasitism by *Trichogramma evanescens* of *Ostrinia nubialis* eggs placed 400m downwind of the point of parasitoid release were equal to parasitism at the release site. These results led to the conclusion that the effective release area for these parasitoids was at least twice the area of the plot releases were made in.

Host specificity is another key component to understanding potential nontarget impacts. Parasitoid species in the genus *Trichogramma* are considered highly polyphagous, together attacking more than 400 species in 203 genera, 44 families, and 7 orders (Pinto 1998, Bao and Chen 1989). However, individual species tend to have narrow host and habitat preferences or climatic tolerances, making them less likely to cause undesired impacts (Orr and others 1999).

Future studies of *Trichogramma* releases in pine plantations should consider the dispersal of parasitoids, and the potential impact of releases on both predatory and herbivorous species within and downwind of release sites. This could be done by estimating parasitism of selected species' eggs when they are placed within plantations and in surrounding habitats into which *Trichogramma* could potentially disperse.

ACKNOWLEDGMENTS

We thank R S Cameron and M Davidson, Union Camp Corporation, for their assistance in locating the sites for this study. This research was funded in part by the Pine Tip Moth Research Consortium: Champion International Corporation; International Paper Corporation; Smurfit-Stone Container Corporation; Union Camp Corporation; USDA Forest Service, Southern Research Station; The Timber Company; and Weyerhaeuser Company. Helpful comments on an earlier version of this manuscript were provided by F. Hain, F. Hastings, and C Nalepa. We are grateful to F Kabiri and J Frandon (BIOTOP, Valbonne, France) for rearing and formulation of *Trichogramma*, and J Shurtleff (NCDA&CS Quarantine Lab) for handling shipments.

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USE OF PHEROMONE TRAPS TO PREDICT INFESTATION LEVELS OF THE NANTUCKET PINE TIP MOTH: CAN IT BE DONE?

Christopher Asaro and C. Wayne Berisford[1]

Abstract—Pheromone traps baited with synthetic baits are used in southeastern pine plantations to monitor the phenology of the Nantucket pine tip moth (*Rhyacionia frustrana* (Comstock)) for timing of insecticide applications. Trap catches of tip moths have been difficult to interpret because they decrease considerably relative to population density from the spring through subsequent generations. Understanding this pattern is important for optimizing trap usage and catch interpretation. Decreased adult longevity during summer was demonstrated and suggested as the primary reason for low catches in hot weather. In addition, methods were developed to utilize pheromone traps for predicting future population density and damage by this pest. Trap catch was strongly correlated with tip moth density and damage within generations. Additionally, trap catch of overwintering moths was a strong predictor of tip moth damage during the subsequent generation.

INTRODUCTION

Currently, pheromone-baited traps are used to capture Nantucket pine tip moth, *Rhyacionia frustrana* (Comstock), for the following purposes: 1) to monitor seasonal activity or phenology (Berisford 1974a, Berisford and others 1992, Canalos and Berisford 1981, Ross and others 1989); 2) to monitor daily activity and behavior (Berisford 1974b, Berisford 1977, Berisford and Hedden 1978, Berisford and others 1979, Canalos and others 1984, Webb and Berisford 1978); and 3) for the initiation of a spray-timing model through the accumulation of degree days (Berisford and others 1984, Fettig and Berisford 1999, Fettig and others 1998, Gargiullo and others 1984, Gargiullo and others 1985, Kudon and others 1988). To date, however, traps have not been used for predicting population density or damage. This would be a powerful tool, enabling managers to make control decisions regarding the next generation based on trap catch data from the current generation of emerging adult moths. Some studies attempting to positively correlate trap catch with insect density or damage have not been successful (Miller and McDougall 1973, Howell 1974, Srivastava and others 1992). One hypothesis frequently cited to explain this is called the "competition effect", which states that as an insect population increases, the number of females in that population will increase and compete with the baits (either sex pheromones or host volatiles) being used in traps (Cardé 1979, Knipling 1979). Nevertheless, many have attempted such studies due to the obvious potential benefits to a pest management system. Promising studies in which some measure of population density or damage has been positively correlated with pheromone trap catch include some important forest pests such as the Douglas-fir tussock moth, *Orgyia pseudotsugata* (McDunnough) (Daterman and others 1979), spruce budworm, *Choristoneura fumiferana* (Clemens) (Allen and others 1986), and gypsy moth, *Lymantria dispar* (L.) (Gage and others 1990, Thorpe and others 1993), as well as some agricultural pests such as the boll weevil, *Anthonomus grandis grandis* (Boheman) (Johnson and Gilreath 1982) and corn earworm, *Helicoverpa zea* (Boddie) (Latheef and others 1993, Drapek and others 1997). The Nantucket pine tip moth is one forest pest for which a sophisticated IPM system is feasible given its importance to intensive forestry, the similarities of intensive forestry to agricultural systems during that portion of the rotation for which tip moths are a problem, and the amount of research that has been devoted to this pest. Therefore, it would seem logical to attempt such a study for the Nantucket pine tip moth.

Before trap catches can be correlated with populations, an important aspect of seasonal tip moth trap catch patterns must be addressed. Tip moths are multivoltine, with three or four generations per year in most of the Southeast (Fettig and others 2000a). If trap catch patterns over an entire season are examined, it is clear that trap catch is not well correlated with density across generations. Typically, trap catches decrease substantially from the first (spring) to the second (early summer) and third (late summer) generations in the Georgia piedmont, even if tip moth populations increase during that period (figs. 1–4). Only in cases where populations increase by four or five fold from spring to summer is their similarity in trap catch between these generations (fig. 2A). It is clear that trap catch and population density across generations are not well correlated. Will this effect our ability to make population predictions?

Four hypotheses have been proposed to explain the phenomenon of decreasing trap catches during the summer generations: 1) The efficacy of pheromone baits decreases rapidly during the summer due to increasing volatility of the pheromone blend at high temperatures. This hypothesis has been rejected since weekly bait replacement during this study failed to increase summer trap catches, and baits have

[1] Asaro, Postdoctoral Research Associate, and Berisford, Research Professor, Department of Entomology, 413 Biological Sciences Building, University of Georgia, Athens, GA 30602.

Citation for proceedings: Berisford, C. Wayne; Grosman, Donald M., eds. 2002. The Nantucket pine tip moth: old problems, new research. Proceedings of an informal conference, the Entomological Society of America, annual meeting. 1999 December 12–16. Gen. Tech. Rep. SRS–51. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 68 p.

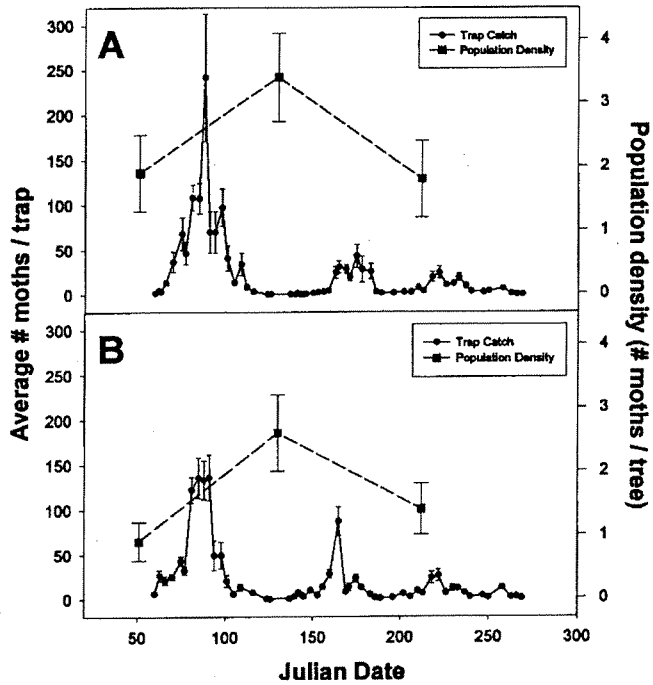

Figure 1—Average number (±SE) of *R. frustrana* males caught in traps and the associated populations density prior to adult emergence from February through September, 1997 at two sites in Clarke and Morgan counties, Georgia A) Harve Mathis Road and B) Bostwick.

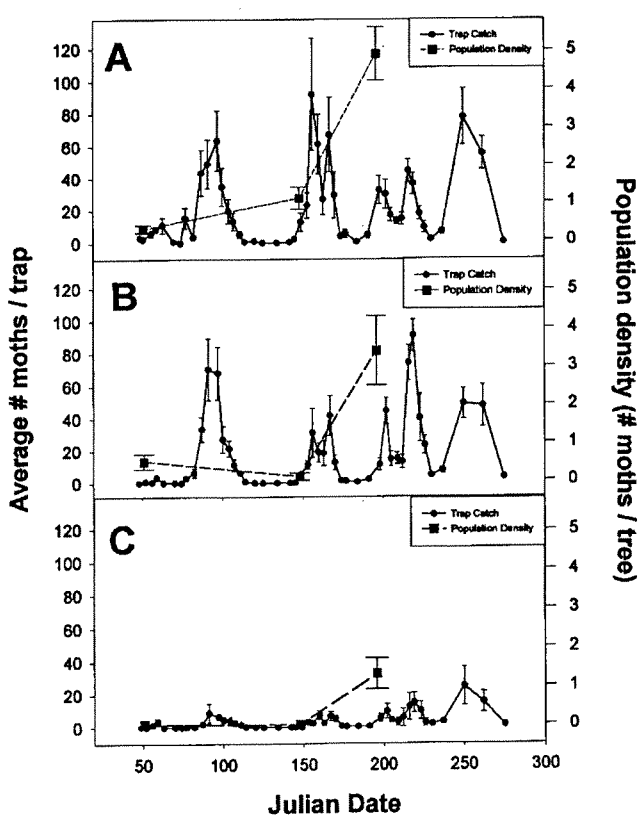

Figure 2—Average number (±SE) of *R. frustrana* males caught in traps and the associated populations density prior to adult emergence from February through September, 1998 at three sites in Oglethorpe county, Georgia A) Lexington, B) Maxeys and C) Arnoldsville.

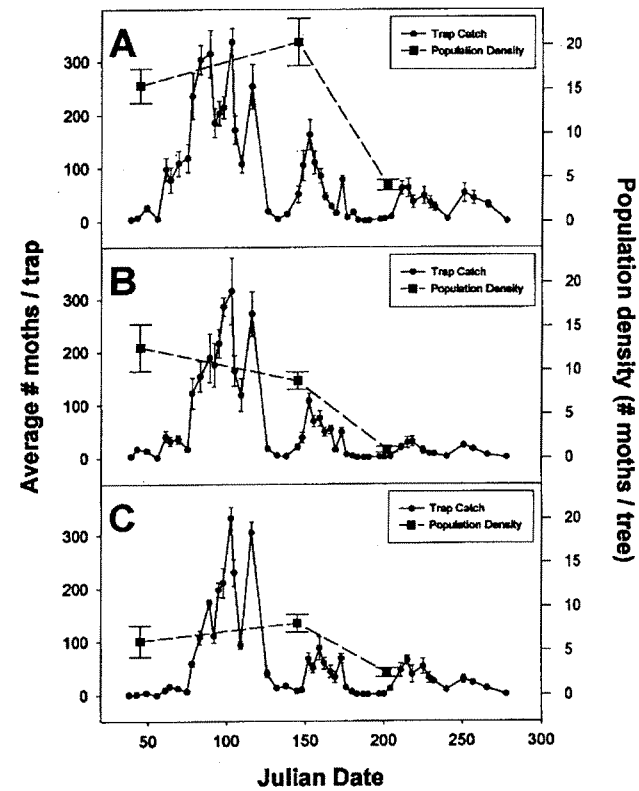

Figure 3—Average number (±SE) of *R. frustrana* males caught in traps and the associated populations density prior to adult emergence from February through September, 1999 at three sites in Oglethorpe county, Georgia A) Lexington, B) Maxeys and C) Arnoldsville.

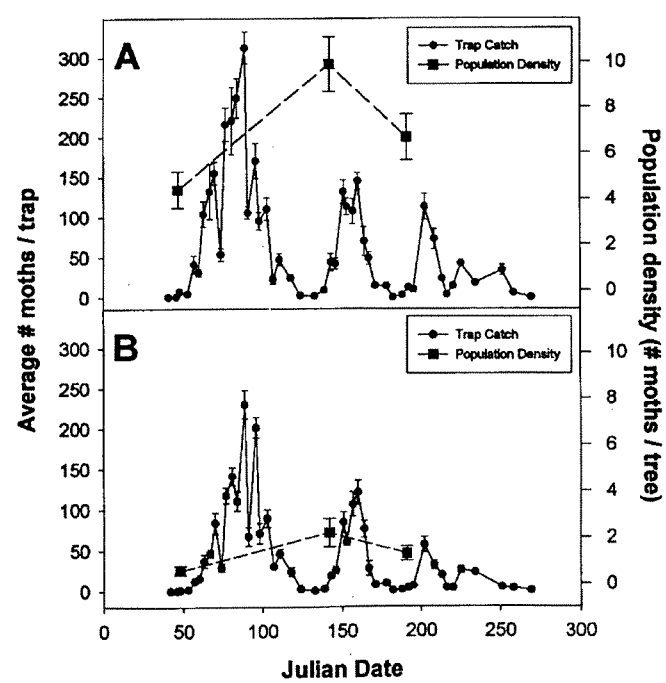

Figure 4—Average number (±SE) of *R. frustrana* males caught in traps and the associated populations density prior to adult emergence from February through September, 2000 at two sites in Oglethorpe county, Georgia A) Lexington and B) Wilkes Farm.

been shown to have maximum attractancy during summer for up to three weeks (Personal communication. Gary L. Debarr. 1997. Southern Research Station, Forestry Sciences Lab, 320 Green St., Athens, GA 30602). 2) Female moths compensate for high summer temperatures by adjusting the pheromone component ratio (20:1 blend of E9-dodecenyl acetate and E9,11-dodecadienyl acetate). Because each pheromone component has a different volatility, under high temperatures, one component may evaporate quicker than the other, changing the ratio significantly to render the baits less effective than competing females. Asaro and others 2001 have shown that there is no significant deviation from the 20:1 ratio in Nantucket pine tip moth pheromone with moths collected from the first and second generation in the Georgia piedmont and coastal plain. 3) During high summer temperatures, male moths have more difficulty locating and following pheromone plumes due to greater heat convection. This hypothesis will not be explored in this discussion. 4) Adult life span decreases during summer due to high summer temperatures, thereby decreasing the probability of catching any given moth during a specific time period. An experiment designed to test this hypothesis is discussed below.

TIP MOTH ADULT LIFE SPAN DURING DIFFERENT GENERATIONS—METHODS

Adult Longevity—Field Experiment

For each of three tip moth generations during March, June, and August 1997 and 1998, adults were reared from clipped pine shoots and collected as they emerged in cages. Up to five newly-emerged moths were placed in waxed paper cans (473 ml, 8.44 cm diameter, Fonda Group Inc., Union, NJ) with each circular end punched out and replaced by a fine mesh material (Saran screen, 12.8 x 12.8 holes / sq cm, Synthetic Industries, Cornelia, GA). Each paper can was placed in a Pherocon 1C® sticky trap (Trece Inc., Salinas, CA) to protect the moths from the elements and ant (Hymenoptera: Formicidae) predation. In 1997, all traps containing cans and moths were hung from trees in a five-year-old loblolly pine (*Pinus taeda* L.) plantation in Oconee County, Georgia and checked daily. In 1998, traps were similarly hung and checked daily within a three-year-old loblolly pine plantation in Oglethorpe County, Georgia.

There was a concern that the interior temperature of the cans would be elevated by being inside the pheromone trap. To check this, measurements on temperature and humidity were taken between 1200 and 1500 EST inside the cans on three separate days during spring (March 11, 23, and 30, n=12 traps per day) and summer (June 16, 22, and 27, n=13 traps per day), and compared to ambient conditions just outside the trap.

Adult Longevity—Lab Experiments

To determine if any differences found in longevity were primarily due to temperature effects, a similar experiment was performed in the laboratory using one spring and one summer cohort of moths by placing them inside the same type of paper cans and exposing them to different constant temperatures within a temperature control unit. The moths were exposed to constant temperatures of 5, 10, 15, 20, 25, 30, 35, and 40°C. Humidity levels were kept between 40–60 percent for all temperature treatments (n=9–41 moths per treatment). The number of moths assigned to each treatment was determined by their availability from the emergence cage.

It is not known whether tip moth adults feed. Many adult moths do not feed (Boggs 1987, Han and Gatehouse 1991), and the short life spans and activity periods of tip moths suggest that they may not either. However, if they visit nectaries or obtain energy from some other source, this would clearly effect the study since moths were prevented from obtaining any source of water or nourishment while enclosed in the cans. Two experiments were conducted in an attempt to test the importance of water or carbohydrates to adult male tip moths. In Experiment 1, life span was monitored under three treatments (n=10 moths per treatment) in which moths were placed individually in glass vials at 20°C with the vial opening capped with dry cotton balls (0.5 cm diameter), cotton saturated with water, and cotton saturated with a two molar sucrose solution. In Experiment 2, male moths were placed individually in vials capped with dry cotton (n=18 moths) or capped with cotton saturated with a two molar sucrose solution (n=17), held at 10°C, and checked daily. To prevent excess moisture from adhering to and overwhelming tip moth adults, all saturated cotton balls were gently squeezed before being placed in a vial.

Statistical Analysis

All tests were performed using SigmaStat 2.0 (Jandel Corporation 1995, San Rafael, CA). Average life spans from the field and lab were compared using Kruskal-Wallis ANOVA on ranks followed by Dunn's test for differences in ranked means. For comparison of internal and external trap conditions, a paired t-test or Wilcoxon signed rank test was used, depending on whether ANOVA assumptions were met. Significance levels for all tests were set at α=0.05.

RESULTS

Adult Longevity—Field Experiment

During 1997 and 1998, male moths lived significantly longer during the first generation than the second and third generations (1997, H=33.08, df=2, P<0.001; 1998, H=48.40, df=2, P<0.001) (fig. 5A). During the first generation in 1997, average (±SD) adult male life span was 7.8 (±4.0) days (n=17) compared with the second and third generations, which averaged 2.3 (±1.0) days (n=29) and 4.2 (±2.1) days (n=20), respectively. In 1998, average adult male life span for the first generation was 12.5 (±5.8) days (n=23) compared with the second and third generations, which averaged 2.8 (±1.1) days (n=33) and 2.8 (±0.9) days (n=24), respectively (fig. 5A).

Adult females from the first generation lived significantly longer than those from the second generation in 1997 (H=19.47, df=2, P<0.001), while in 1998 females from the first generation lived significantly longer than those from the second and third generations (H=33.39, df=2, P<0.001) (fig. 5B). During the first generation in 1997, average (±SD) adult female life span was 15.3 (±5.6) days (n=17) compared with the second and third generations, which averaged 6.4 (±2.8) days (n=29) and 8.6 (±2.1) days (n=20), respectively. In

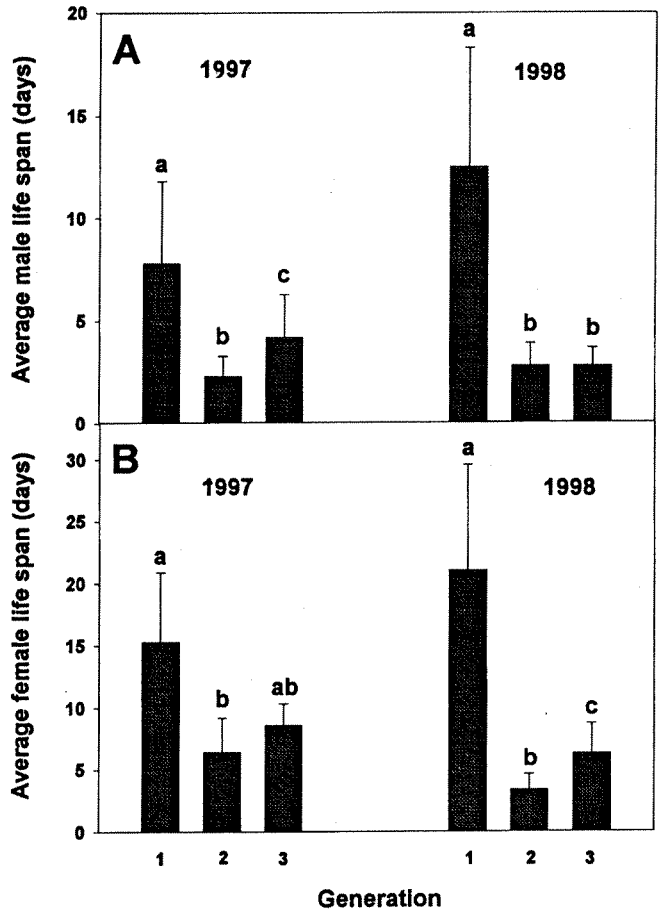

Figure 5—Average (±SD) life span of each generation of adult *R. frustrana* males (A) and females (B) in a loblolly pine plantation near Athens, Georgia during 1997 and 1998. Within each year, means followed by the same letter are not significantly different at a=0.05 (Dunn's Method).

1998, average adult female life span for the first generation was 21.0 (±8.6) days (n=23) compared with the second and third generations, which averaged 3.4 (±1.3) days (n=33) and 6.3 (±2.4) days (n=24), respectively.

Average (±SD) daily temperature and humidity during the 1997 field experiment was 15.1°C (±2.8) and 57.0 percent (±16.7), respectively, for first generation moths (March 18 to April 11), 26.1°C (±1.5) and 74.8 percent (±5.7) for second generation moths (June 19 to July 6), and 25°C (±2.7) and 64.5 percent (±7.8) for the third generation moths (August 14 to September 7). Similarly, the average daily temperature and humidity during the 1998 field experiment was 13.1°C (±4.7) and 69.5 percent (±17.0) for the first generation (February 28 to May 4), 25°C (±3.0) and 66.2 percent (±9.2) for the second generation (June 4 to June 16), and 26.6°C (±1.7) and 64.0 percent (±9.2) for the third generation (July 23 to August 6).

Internal trap temperatures were 1.0 and 0.5°C higher, respectively, than ambient during spring (t= -3.54, df= 1, P=0.005) and summer (t= -3.18, df=12, P=0.008), while internal humidity was 2.8 percent lower than ambient during spring (W = -52.0, df=11, P=0.042). However, these differences were so minor that they are not thought to have had any influence on adult longevity (table 1).

Adult Longevity—Lab Experiments

For first generation males, average life span (±SD) at 5, 10, 20, 30, 35, and 40°C treatments was 8.2 (±3.1) (n=15 males), 7.9 (±3.2) (n=22), 4.4 (±2.4) (n =29), 1.5 (±0.7) (n=20), 1.0 (±0.3) (n=41), and 0.7 (±0.3) (n=20) days, respectively. The first three treatments were all significantly different from the latter three (H=106.99, df=5, P<0.001) (fig. 6A). For second generation males, average life span (±SD) at 5, 15, 25, 30, and 35°C treatments was 10.8 (±1.9) (n=15 males), 4.3 (±1.4) (n=20), 2.4 (±0.8) (n=10), 2.6 (±1.1) (n=9), and 1.6 (±0.8) (n=10) days, respectively. Only the first treatment was significantly different from the latter four treatments (H=47.93, df=4, P<0.001) (fig. 6A).

No significant differences in adult male life span were found for any of the treatments involving dry cotton, cotton saturated with water, or cotton saturated with a two molar sucrose solution (Experiment 1, H=1.20, df=2, P=0.549; Experiment 2, T=344.5, P=0.210) (fig. 6B). In Experiment 1, moths in the dry cotton treatment lived an average of 3.6 (±1.4) days, those in the wet cotton treatment lived 4.0 (±0.8) days, and those in the sugar water treatment lived 3.5

Table 1—Comparison of ambient temperature (°C) and humidity with the interior of traps used in the study. Within each season and variable measure, means followed by the same letter are not significantly different

	Spring		Summer	
	Temperature	Humidity	Temperature	Humidity[a]
		Percent		*Percent*
Trap Interior	15.8 a	43.6 a	31.7 a	52.7 a
Ambient (outside trap)	14.8 b	46.4 b	31.2 b	52.2 a

[a] Paired t-test or Wilcoxon signed rank test, a = 0.05).

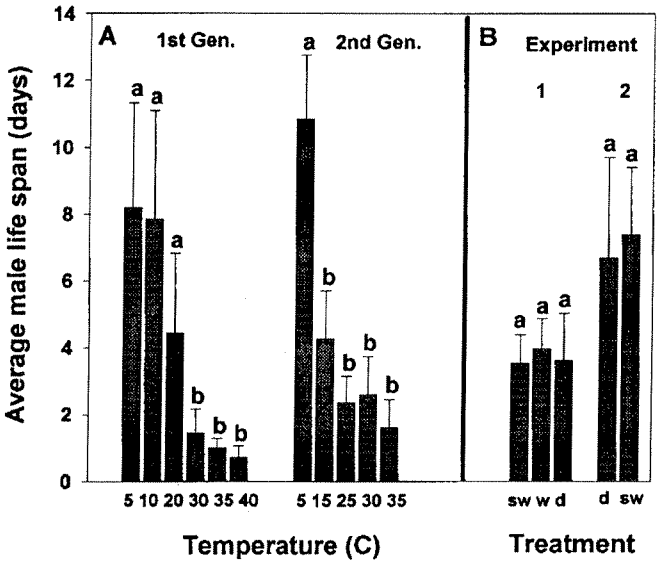

Figure 6—(A) Average (±SD) life span of adult *R. frustrana* males under different constant temperatures using moths from the first and second generations and (B) two experiments comparing male moth life span under different treatments (sw=sugar water, w=water only, d=dry) and constant temperatures (Experiment 1 - 20°C, Experiment 2 - 10°C).

(±0.8) days. In Experiment 2, moths in the dry cotton treatment lived 6.7 (±3.0) days while those in the sugar water treatment lived 7.4 (±2.0) days (fig. 2B).

DISCUSSION

During both years of the field study, it was demonstrated that Nantucket pine tip moth adults do experience decreased longevity during the second and third generations when temperatures are significantly warmer. Although other environmental or physiological factors may influence adult longevity, temperature appears to be the most important factor. In the laboratory experiments, humidity was kept between 40–60 percent in the temperature control units, and moths kept in vials capped with saturated cotton did not live longer than those in vials capped with dry cotton under the same constant temperatures. Although humidity was not measured inside the vials, it was likely substantially higher in those that were capped with saturated cotton since tiny droplets of condensation were sometimes observed in these vials. Furthermore, average humidity levels during the 1997 field experiment were lower in spring than in summer, while in 1998 they were almost the same between seasons. Since these variations were not correlated with the seasonal change in adult longevity, it appears that humidity is not as important as temperature in affecting adult life span. Although the environment of the paper cans was a concern, the small differences in temperature and humidity within the can and the ambient conditions did not appear to have any effect on life span.

Butler and Foster (1979) showed that adults of the pink bollworm, *Pectinophora gossypiella* (Saunders) (Lepidoptera: Gelechiidae), held at constant temperatures lived longer than at comparable, fluctuating temperatures. Pilon (1966) also demonstrated shorter life span under fluctuating than constant temperatures for both sexes of the Swain jack pine sawfly. For the Nantucket pine tip moth, life spans in the field experiment closely matched those in the laboratory experiment under similar average temperatures (figs. 5 and 6). The constant temperatures used in the lab experiments did not appear to effect this species.

Other factors that may have influenced adult longevity include the moths inability to fly very far and expend metabolic energy (Boggs 1987), an inability to mate, and an inability to feed or drink. Nantucket pine tip moths mate infrequently and produce few viable eggs when caged in the laboratory or confined to small spaces (Cresswell and others 1971, Richmond and Thomas 1977). Partridge and Farquhar (1981) demonstrated that sexual activity reduces the life span of male fruit flies (Diptera: Tephritidae) while Moscardi and others (1981) showed that unmated females of the velvetbean caterpillar lived significantly longer than mated females at a given temperature. Although male and female tip moths were mixed together in half of the paper cans placed in the field, there were no differences in the life span of either sex compared with those that were placed in same-sex cans (data not shown). The extent to which adult tip moths feed or drink, if at all, is unknown. In their studies of the pine beauty moth, Leather and Burnand (1987) reported that unfed female adults had a shorter life span. Leahy and Andow (1984) showed that diets with sugars significantly increased oviposition period, fecundity, and adult longevity in the European corn borer, *Ostrinia nubilalis* (Hübner) (Lepidoptera: Pyralidae). Howell (1981) observed a 6–12 day increase in adult longevity of the codling moth when provided water, carbohydrate, or a carbohydrate-protein solution, but no increase in mating, oviposition, or egg viability. Kira and others (1969) reported that water was the most important feeding requirement for adults of the European corn borer. Our lab experiments involving sugar solution (fig. 6B) were inconclusive. Although there were no differences between treatments, we can only conclude that adults do not feed or that they were not stimulated to do so under these specific conditions. It is clear, however, that addition of food and water did not affect the life span of adult moths in captivity. There are a number of species of moths that do not feed as adults (Boggs 1987, Han and Gatehouse 1991). Indeed, in many species of Lepidoptera, the maximal number of eggs an individual can lay is proportional to the amount of stored nutrient reserves acquired during larval feeding (Engelmann 1970). In other species, carbohydrates obtained during adult feeding are either used immediately in oogenesis or stored as glycogen in the fat body and used after hydrolysis. Glycogen seems to be involved in the maintenance of body weight and oocyte production (Kozhantshikov 1938, Chapman 1982).

There is a pronounced difference in adult longevity between spring and summer. This helps to explain why summer trap catches of the Nantucket pine tip moth often drop precipitously from spring to summer despite constant or increasing populations. This should be taken into account when using traps to monitor moths and making population estimates based on trap catch.

ESTIMATING NANTUCKET PINE TIP MOTH POPULATIONS FROM TRAP CATCH - METHODS

This study was conducted over a 4-yr period from 1997–2000. Ten study sites of two or three-yr-old loblolly pine (*Pinus taeda* L.) plantations were used in the Georgia piedmont within Clarke, Morgan, and Oglethorpe counties, where there are three tip moth generations per year. Plantation size varied from 3 to 20 ha and tree density varied from 1.8 x 3 m (1,794 trees / ha) to 1.8 x 3.7 m (1,495 trees / ha).

Pheromone Trap Catch

A 2 ha rectangular plot was established within each plantation. Six Pherocon 1C® wing traps baited with red rubber septa loaded with synthetic *R. frustrana* pheromone (Trece Inc., Salinas, CA) were placed on each plot, one in each corner and one midway along each of the longer two sides. Traps were at least 30 m from the plantation edge and more than 30 m apart. Baits were replaced weekly to insure high efficacy. The number of males trapped was recorded, and insects were removed or trap bottoms replaced every 3–5 days from February to October during each year of the study.

Population Density and Damage Estimation

Prior to the onset of adult emergence for each generation, 40 trees were randomly selected within each plot. Gargiullo and others (1983) showed that this sample size is adequate for making estimates of per tree populations for all tip moth life stages using a two-stage cluster sampling method. For this procedure, each tree was divided into two strata, and the total number of shoots per stratum recorded. Three shoots from each stratum were randomly selected, clipped, and collected in paper bags. A shoot was defined as being at least 5 cm long and terminating in a bud. In tree strata containing more than 20 shoots, shoots were clustered together into equivalent sampling units so that three of these clusters represented a significant proportion (10–20 percent) of the total number of shoots within each stratum. This sampling procedure was designed to be quick, efficient, and robust to the extensive variation found in tree size and form within a plantation.

Clipped shoots were dissected and the number of larvae and pupae and their condition (apparently healthy, parasitized, diseased, or dead) was recorded. Using the methods of Gargiullo and others (1983), the number of viable moths per tree was estimated for each generation. It was assumed that all apparently healthy larvae and pupae would persist in this condition until they emerged as adults. This density estimate was compared with the average number of moths subsequently caught during the entire trapping period within each generation and each site. Dead or nonviable life stages were not included in the density estimate since they would not contribute to the adult population.

Sampling was timed so that the maximum number of pupae would be collected before adult emergence began for each generation. This is not difficult to do for the spring generation, when all overwintering moths are simultaneously in the pupal stage. Unparasitized pupae stand a good chance of surviving to adulthood since most parasitism occurs during the earlier stages of tip moth development (Gargiullo and Berisford 1983). Therefore, viable pupae should provide a reasonable estimate of adult population density to relate to adult trap catch. For later generations, however, development is somewhat staggered, with several developmental stages often present at the same time. Therefore, it was not possible to obtain samples for these later generations prior to adult emergence that did not include larvae.

In addition to estimates of population density, whole tree damage estimates were also obtained from each site prior to each adult emergence period. For each of the 40 randomly sampled trees within a plot, the total number of shoots per tree and the total number of damaged shoots per tree (indicated by a visible pitch mass near or on the bud and dead or dying needles) were counted. In this case, a shoot was defined as being at least 2.5 cm long and terminating in a bud. No clustering of shoots was done, as above, for these estimates.

Statistical Analysis

Relationships between population density, host damage and trap catch were described with linear or non-linear regression models using Sigmaplot 4.01 (SPSS Inc. 1997, Chicago, IL). Scatter plots were examined prior to regression to determine the most appropriate model, which was evaluated by looking at the r^2 value, heteroscedasticity and whether the model was likely to be robust to other similar data sets (Sokal and Rohlf 1995).

RESULTS AND DISCUSSION

During 1997, 1999, and 2000, pheromone trap catches generally decreased dramatically from the first adult generation through subsequent generations despite considerable increases in population density, mostly between the overwintering and first generation broods (fig. 1A,B; fig. 3A,C; fig. 4A,B). This pattern was not as evident in 1998, however, when spring populations were considerably lower than the two subsequent generations and populations were low overall (fig. 2A,C). In one case, the second trap catch peak was slightly greater than the first, spring peak (fig. 2A), but there was an almost four-fold population increase during this period. In general, the magnitude of the second and third adult emergence peaks relative to population density were comparable to each other but not with that of the first emergence peak. For example, the mean (±SE) ratio of total trap catch to population density (number of moths per tree) was 707 (±216) for the first adult emergence peak, 114 (±33) for the second peak, and 97 (±13) for the third peak.

At most sites in all years, trap catches show a small but distinct fourth emergence peak at Julian dates 240–260 (figs. 1–4). Although only three generations were reported in this part of Georgia (Fettig and others 2000a), a small proportion of the third generation population may not diapause, and may emerge in the fall under favorable climatic conditions. Larvae from these adults apparently do not survive so late in the season (Kudon and others 1988). The late catches were combined with the third generation catches for convenience because it would be very difficult to

tell which moths, if any, represented a partial fourth generation.

A strong positive relationship was found between total trap catch and tip moth population density and damage, respectively, for the first generation (fig. 7A, y=2815.277 [SE=339.584]x)/(2.014 [SE=0.790]+x, p<0.001); figure 7B, y= (4660.129 [SE=1698.476]x)/(61.730 [SE=40.660]+x, p<0.001)), and a moderately strong positive relationship between these parameters for the second (fig. 7C,

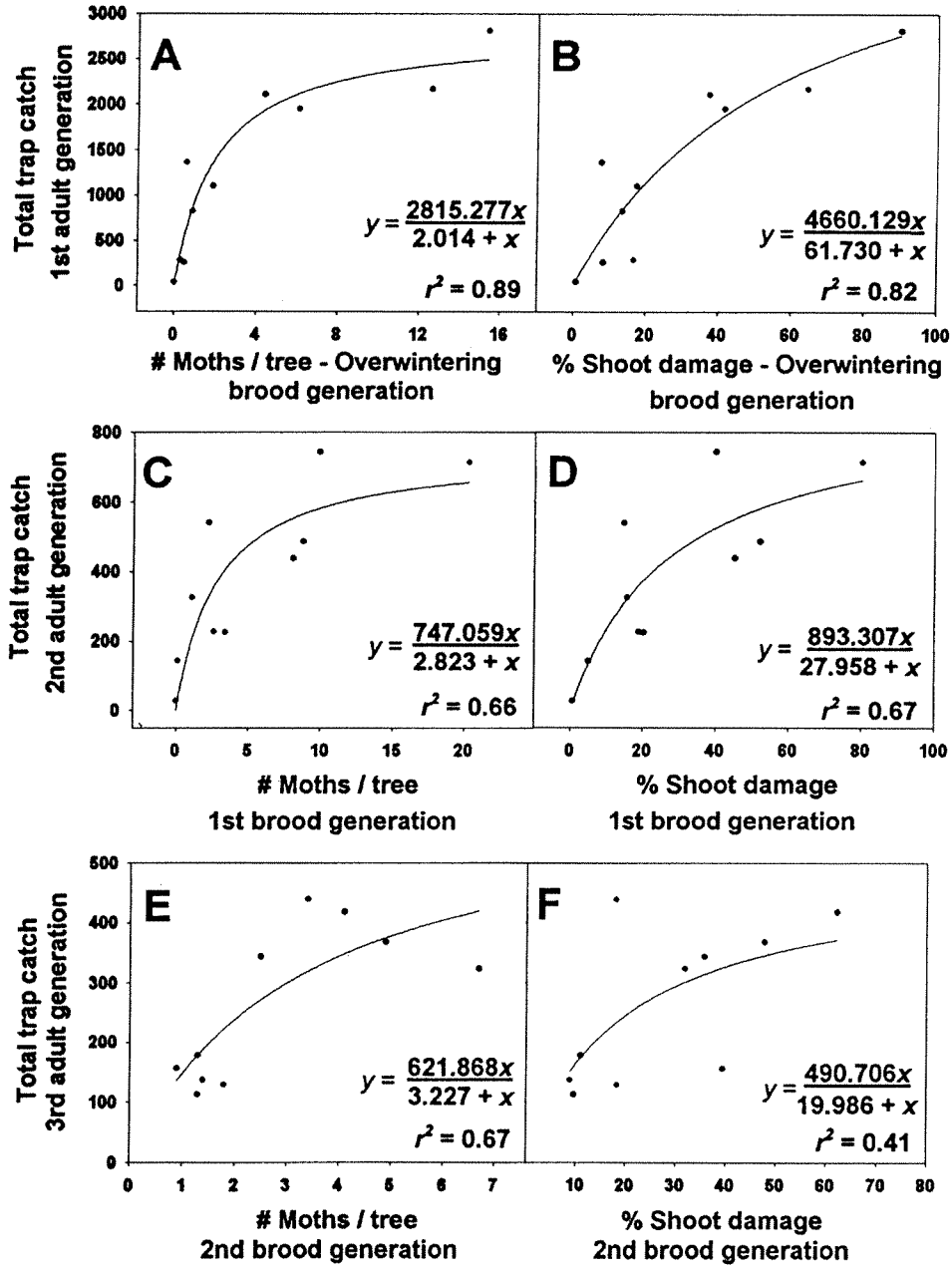

Figure 7—Regression analyses modeling the relationship between A) *R. frustrana* overwintering brood population density and total trap catch during the first adult generation, B) average percent shoot infestation of the overwintering brood and total trap catch during the first adult generation, C) *R. frustrana* population density of the first generation brood and total trap catch during the second adult generation, D) average percent shoot infestation of the first generation brood and total trap catch during the second adult generation, E) *R. frustrana* population density of the second generation brood and total trap catch during the third adult generation, and F) average percent shoot infestation of the second generation brood and total trap catch during the third adult generation. A hyperbola was used for each model. Normality and homoscedasticity were present in all models.

y=(747.059 [SE=170.178]x)/(2.823 [SE=1.998]+x, p=0.004); Figure 7D, y=(893.307 [SE=300.707]x)/(27.958 [SE=21.535]+x, p=0.004)) and third (fig. 7E, y= (621.868 [SE=206.470]x)/(3.227 [SE=2.155]+x, p=0.004); Figure 7F, y=(490.706 [SE =186.625]x)/(19.986 [SE=18.692]+x, p=0.045)) generations. The relationship between trap catch and tip moth density (average number of moths per tree) was best fit by a hyperbola, which explained 89, 66, and 67 percent of the variation for the first, second, and third generation models, respectively (fig. 7A, C, E). Similarly, the relationship between trap catch and damage (average percent of shoots infested per tree) was best fit by a hyperbola, which explained 82, 67, and 41 percent of the variation for the first, second, and third generation models, respectively (fig. 7B, D, F). The hyperbolic pattern of these data suggest that trap saturation may occur at very high densities. Ramaswamy and Cardé (1982) reported that Pherocon 1C® trap efficiency decreased with increasing catch of male spruce budworms (*Choristoneura fumiferana*) due to a reduction of sticky surface area within the trap. Increased competition from calling females may also cause trap catch to level off at high densities (Knipling 1979, Unnithan and Saxena 1991). However, trap saturation was not apparent within the range of densities seen in this study.

The fate of the larval instars sampled is much less certain than that of pupae due to a greater potential for mortality factors such as parasitism and resinosis (Gargiullo and Berisford 1983). Therefore, population density estimates of viable moths from samples collected during the summer generations, which included larvae and pupae, should be less accurate than the estimates for the spring generation. Hence, it should become more difficult to relate population density to trap catch during the summer generations.

Density estimates were not better correlated with trap catch than damaged shoots, except during the third generation. This was unexpected because damaged shoots often contain dead or parasitized moths that will not contribute to trap catch tallies. Therefore, shoot damage as a population estimate was originally thought to be less precise. Percent shoot damage can sometimes be poorly correlated with trap catch (fig. 7F); two outlying points cause this regression to be substantially poorer than the associated regression using tip moth density (fig. 7E). One of these outliers had 89 percent tip moth mortality within the damaged shoots during the third generation (data not shown). This produced an overestimate of tip moth populations. When shoots are sampled and dissected, however, the number of non-viable tip moths can be determined and a more realistic association with trap catch can be made. The other outlier was caused by the opposite phenomenon, in which trap catch produced an underestimate of the population. It only takes one or two such outliers to substantially weaken the strength of a regression model. We could not determine whether the poorer correlation in the third generation is biologically significant or simply happenstance.

Using damage as an indicator of trap catch rather than density does seem feasible given the outcome of the regression models from the first two generations. Furthermore, damage estimates are significantly less labor intensive, can be done quickly in the field, and require much less expertise than randomly sampling shoots, dissecting them in a laboratory, and determining the extent of tip moth parasitism and mortality. Therefore, future studies should associate trap catch with percent shoot damage per tree, which is more easily obtained and meaningful to forest managers.

Although trap catch appears to be closely linked with population density and damage within generations (fig. 7), the predictive value of these models is limited. It is more desirable to predict what tip moth populations will be in the next generation based on trap catch during the current generation. Total trap catch during the first adult generation is a strong predictor of tip moth density (fig. 8A, y=0.006 [SE=0.001]x - 2.175[SE=1.512], r^2=0.83, p<0.001) and damage (fig. 8B, y=0.024 [SE=0.003]x - 2.022 [SE=5.114], r^2=0.87, p<0.001) during the next generation using a linear model. However, total trap catch during the second adult generation was a poor predictor of density (fig. 8C, y =0.004 [SE=0.002]x + 1.299 [SE=1.102], r^2=0.24, p=0.146) and damage (fig. 8D, y=0.047 [SE=0.021]x + 10.270 [SE=9.463], r^2=0.38, p=0.059) during the subsequent generation. In both cases, however, trap catch predicted damage more accurately than it predicted density. No attempt was made to use the third adult generation trap catch to predict subsequent damage or density of the overwintering brood (next years first adult generation). The extended and unpredictable overwintering period usually results in greater fluctuations in tip moth density, tip moth damage, and mortality factors compared with fluctuations within the same year (data not shown), making it inherently more difficult to predict what will happen during the winter. Furthermore, the sites in this study for which measurements were carried over a second or third year (Arnoldsville, Maxeys, Lexingtion) show a very poor correlation between third adult generation trap catch and subsequent density (r = 0.36) and damage (r = 0.33) of the overwintering brood.

Third generation population density and damage is inherently difficult to predict using traps. This is not surprising given that spray-timing models are also significantly less accurate during the third generation. Fettig and others (2000b) reported control as low as 55.5 percent for the third generation when control for the first and second generations averaged 90.4 percent and 77.6 percent, respectively. This most likely occurs because adult emergence during the last generation is much more protracted than earlier generations (figs. 1–4) and there is a progressive decrease in the synchrony of life stages throughout the year. Hence, avoiding chemical control of the third generation brood has been proposed (Fettig and others 2000b).

Trap catch tallies used in the regression models (fig. 8) were totals for the entire adult emergence period. This is not entirely adequate if trap catch is to be used to predict numbers or damage for subsequent generations because in order to count total moths for the entire emergence period, one must pass the optimum spray date for the next generation. This problem can be overcome if one assumes that a certain percentage of the total moths to emerge will be caught prior to the spray date. Spray dates for many areas of the southeast can be determined following the

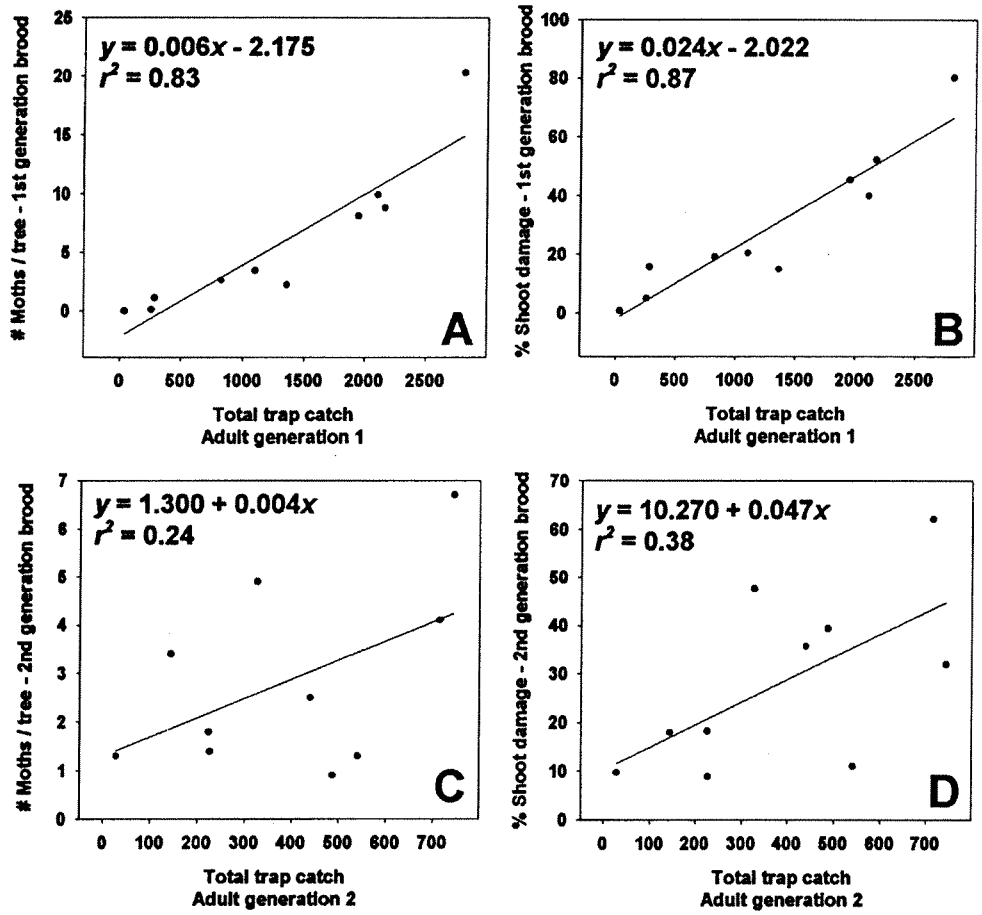

Figure 8—Regression analyses modeling the relationship between A) total trap catch during the first adult generation and *R. frustrana* population density during the first generation brood, B) total trap catch during the first adult generation and average percent shoot infestation during the second generation brood, C) total trap catch during the second adult generation and *R. frustrana* population density during the second generation brood, and D) total trap catch during the second adult generation and average percent shoot infestation during the second generation brood.

methods of Fettig and others (2000a) and are based on the accumulation of degree-days, which relate to the developmental rates of *R. frustrana* following oviposition. In the current study, the mean (±SD) percentage of total moths caught prior to the spray date was 65.3 percent (±14.6) for the first adult generation, 85.1 percent (±6.7) for the second adult generation, and 47.9 percent (±23.1) for the third adult generation. During three of the four years of this study, these percentages were fairly consistent (data not shown). Variation can be considerable, however, since trap catches are strongly influenced by temperature and the spray date is determined through the accumulation of degree-days (Fettig and others 2000b). Nevertheless, application of these percentages to the x-axis of figure 8 will provide predictive trap catch numbers prior to the spray date. For example, figure 8B demonstrates that catching 1836 moths (65.3 percent of 2812) prior to the predicted optimum spray date during the first adult generation would result in 80 percent shoot damage per tree during the subsequent generation. Similarly, catching 539 moths (65.3 percent of 825) prior to the spray date during the first adult generation would result in approximately 20 percent shoot damage per tree during the subsequent generation. In the former case, chemical control would probably be warranted, while in the latter case it may not be. Although a damage threshold for *R. frustrana* has not been established, recent studies suggest that damage levels of less than 40 percent infested shoots may cause significant growth loss (Nowak and Berisford 2000, Fettig and others (2000b), Asaro and Berisford, unpublished data). Therefore, Figure 8B suggests that trap catches above 1,000 moths (approximately 65 percent of 1500) prior to the spray date would warrant chemical control to avoid significant volume reductions.

These models should be used with caution since they have not been validated in other areas. Trap catch numbers may be substantially different in other regions since they are strongly influenced by temperature. Consideration of tree

age or size may be important, particularly in areas where pines grow rapidly. For example, x percent shoot damage on a tree that is 1 m tall will harbor a much smaller tip moth population than x percent shoot damage on a tree that is 3 m tall, assuming parasitism rates are similar. Therefore, if tree age or height is not taken into account, very inaccurate predictions of tip moth infestation based on trap catch may result. In the current study, no attempts were made to stratify plantations by age, size, tree density or tree height (although the range of these parameters was limited) because of the small number of sites and a desire for these prediction models to be widely applicable to any and all site conditions within a region. These specific models are not necessarily appropriate for every region and circumstance, however, and validation will be a necessary next step before their widespread use is adopted.

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NANTUCKET PINE TIP MOTH, *RHYACIONIA FRUSTRANA*, LURES AND TRAPS: WHAT IS THE OPTIMUM COMBINATION?

Gary L. DeBarr, J. Wayne Brewer, R. Scott Cameron and C. Wayne Berisford[1]

Abstract—Pheromone traps are used to monitor flight activity of male Nantucket pine tip moths, *Rhyacionia frustrana* (Comstock), to initialize spray timing models, determine activity periods, or detect population trends. However, a standardized trapping procedure has not been developed. The relative efficacies of six types of lures and eight commercial pheromone traps were compared in field tests in Alabama, Georgia, South Carolina, and Virginia. Additional factors, including trap color, lure longevity and loading rates and ratios were also tested. These tests demonstrate that lures and/ or traps have a pronounced effect on male moth catches. The Pherocon 1C® wing trap was the most effective. White traps were slightly better than colored traps. Pherocon 1C® wing traps baited with commercial Scentry®, Ecogen® or Trécé® lures caught the greatest numbers of moths.

INTRODUCTION

Female NPTM Sex Pheromones and Male Response

Larvae of the Nantucket pine tip moth (NPTM), *Rhyacionia frustrana* (Comstock), bore into and kill the shoots of loblolly pine, *Pinus taeda* L.(Yates 1960). NPTM mate shortly after they emerge from infested shoots. Female moths produce small quantities of sex pheromones that attract conspecific males for mating (Manley and Farrier 1969). Females exhibit crepuscular behavior and begin emitting their pheromones ("calling") at dusk (Berisford 1974; Berisford and others 1979). Their calling period lasts for two hours or less each day. It ends just before a sympatric species, the pitch pine tip moth, *R. rigidana* (Fernald), begins its calling period at about 1 hr after the onset of darkness (Berisford 1988). In the spring, peak male flight activity and the highest NPTM catches in pheromone-baited traps occur just before dark (Berisford and Brady 1972). NPTM fly when temperatures equal or exceed 10 EC (50 EF) (Webb and Berisford 1978). In the summer, when average temperatures are higher, male flight is later in the evening and less intense.

Berisford and Brady (1972) noted that catches of NPTM during the emergence of the overwintering generation in March and April were higher than those of later generations. They speculated that overwintering females might produce and release more pheromone than summer females. Alternatively, male response may be stronger in the spring, than during the summer, which would provide an advantage by insuring mating when NPTM populations are low. They also suggested that male catches in traps may decrease when large numbers of feral females are present to compete with the traps. Recent investigations have shown that catches in traps baited with synthetic pheromone lures are also lower during later tip moth generations even though populations are high (Asaro and Berisford 2001a).

The Pheromones

NPTM females produce a two-component sex pheromone (Berisford and Brady 1973) and their pheromone glands contain only about 20 nanograms (ng) of attractive components. Hill and others (1981) identified a straight-chain 12 carbon monoene acetate, (*E*)- 9-dodecen-1-yl acetate, (*E*9-12:OAc), as the major pheromone component in female gland extracts and a straight-chain 12 carbon diene acetate, *(E,E)*-9,11-dodecadien-1-yl acetate, (*E9,E*11-12:OAc), as a minor component. The components, *E*9-12:OAc and *E9,E*11-12:OAc occur in a 96:4 ratio in the female glands. Field tests in the Georgia Piedmont during first and second NPTM generations demonstrated that a synthetic mixture of these two compounds is as effective in attracting NPTM males, as conspecific females. Three other compounds, dodecan-1-ol, *E*-9-dodecenol (*E*9-12-OH) and dodecan-1-yl acetate, were present in the female glands but their role, if any, in pheromonal communication by NPTM remains unknown.

NPTM Lures and Traps

Tests conducted in the Georgia Piedmont during the first and second generations of NPTM show that 1.0 mg of *E*9-12:OAc plus 0.025-0.050 mg of *E*9,*E*11-12:OAc dispensed on a red rubber septum was an effective lure for NPTM (Hill and others 1981). Based upon this research, several NPTM lures are now available from commercial sources. These lures contain synthetic *E*9-12:OAc and *E*9,*E*11-12:OAc impregnated into rubber septa, plastic laminates, or dispensed from hollow glass fibers. Since the original work of Hill and others (1981), no additional field tests have been conducted to compare the performance of various lures,

[1] DeBarr, Research Entomologist (Retired), Southern Research Station, USDA Forest Service, 320 Green Street, Athens GA 30602-2044; Brewer, Professor of Entomology, Department of Entomology, Auburn University, Auburn, AL 36849; Cameron, Forest Health Manager, International Paper Company, PO Box 1391, Savannah, GA 31402; and Berisford, Professor of Entomology, Department of Entomology, University of Georgia, 413 Biological Science Bldg., Athens, GA 30622-2603.

Citation for proceedings: Berisford, C. Wayne; Grosman, Donald M., eds. 2002. The Nantucket pine tip moth: old problems, new research. Proceedings of an informal conference, the Entomological Society of America, annual meeting. 1999 December 12–16. Gen. Tech. Rep. SRS–51. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 68 p.

longevity of the lures, and optimum dosages and ratios the two NPTM pheromone components in other parts of the range of NPTM or for later generations. Two types of commercially available sticky traps, delta-style and wing-style, are currently used for NPTM. Tests have not been conducted to compare the efficiency of these two traps or others types of commercially available traps.

The efficiency of lures for NPTM depends on the amount and ratios of the two synthetic pheromones released. Lures that release too little pheromone will not attract moths; those that release too much may inhibit them. Research on lures for the coneworms, *Dioryctria* spp., clearly showed that catches of male moths in pheromone-baited traps are related to lure release rates (Meyer and others 1982, 1986). Lures that release the wrong ratios of the two pheromone components may also be unattractive (Hill and others 1981). Good lures can be more attractive than females. The best lures for the European pine shoot moth, *R. buoliana* (Schiffermuller), which uses the same major pheromone component as NPTM, attract 20 times more males than a single female moth (Smith and others 1974, Daterman 1974).

The amount of pheromone released per female NPTM and whether the rate of release and ratio of the two pheromones is constant for each generation is unknown. Females in later generations may be able to maintain the 96:4 natural blend, while compensating for higher ambient field temperatures by releasing more pheromone than at low temperatures. We also do not know if the quantities and natural blend of two components released by NPTM females in Piedmont Georgia are the same in other parts of its range.

Also unknown is how accurately the synthetic pheromones in NPTM lures emulate the natural blend released by females. Formulating NPTM lures is complicated because the attractive blend requires two components, and the minor component is an unstable diene. Factors that affect the rate of loss and stability of synthetic pheromones from NPTM lures include chemical structure of the pheromone, ambient field temperatures, rate of air movement over the lure, lure type, and dosage. The unique volatility of each component of Lepidoptera pheromones is determined by the length of the carbon chain, the number and position of double bonds, and the functional group. *E*9-12:OAc and *E9,E*11-12:OAc each have their own vapor pressure constants, which determine their evaporation rates from NPTM lures. Local field conditions, primarily the seasonal and diurnal fluctuations in ambient temperatures, greatly affect the pheromone loss rates and half-life of NPTM lures at any given field site and for each NPTM generation. For example, over an 8 day period polyvinyl chloride (PVC) baits lose 18 percent of their *E*9-12:OAc with daily maximum temperatures of 20–23 EC (68–74 EF), and 37 percent with daily maximum temperatures of 27–29 EC (80–85EF) (Daterman 1974). On hot summer days NPTM lures emit more pheromone than on cooler spring or fall days. Unless the half-life for *E9,E*11-12:OAc and *E*9-12:OAc are the same for a lure, the ratio of two components may change, reducing its attractiveness.

Natural or butyl rubber septa (laboratory stoppers), PVC dispensers, and laminated dispensers, such as Hercon Luretapes®, all emit pheromones by a first-order process, where the rate of evaporation is directly proportional to the amount of pheromone remaining in the lure (Butler and McDonough 1981). Natural red rubber septa are commonly used to prepare lures with Lepidoptera sex pheromones for monitoring traps. Natural red rubber septa have a large loading capacity (> 75 mg) and are composed of a cross-linked polymer that releases most straight-chain pheromones at moderate to very slow rates providing lures with a long half-life (Butler and McDonough 1981). Septa are inexpensive and can be easily loaded without highly specialized equipment. The major component of the NPTM pheromone, *E*9-12:OAc, has a 12-carbon chain and a half-life of 38 days on red natural rubber septa (Butler and McDonough 1981). The half-life for *E*9-12:OAc is almost 3 times greater on natural red rubber septa, as on PVC baits (Daterman 1974). We are unaware of any published half-life data for the minor component of the NPTM pheromone, *E9,E*11-12:OAc, on septa or PVC lures. If the half-life for *E9,E*11-12:OAc on a lure is the same as for *E*9-12:OAc the ratio of these two components released from the lure will remain constant through time. Otherwise, the ratio will change.

The dosage of 1 mg per NPTM lure (Hill and others 1981) is relatively high compared to many other forest Lepidoptera. A plastic laminate lure for gypsy moth, *Lymantria dispar* (L.), has 0.5 mg of pheromone (Leonhardt and others 1992), a red septum lure for the webbing coneworm, *D. disclusa,* has 0.1 mg of pheromone (Meyer and others 1982), and a septum lure for the spruce seed moth, *Cydia strobilella* (L.) has only 0.0003–0.003 mg (Grant and others 1989). Lures of PVC (or other non-cross-linked polymer) are useful for insects which respond to relatively high amounts of pheromone because the desired release rate can be obtained with a lower dosage per lure (Butler and McDonough 1981). The optimum release rate of *E*9-12:OAc from PVC lures was 5–56 ng/min for *R. buoliana* (Daterman 1974), but the optimum release rate for NPTM is unknown. Release rates of 30 ng/h are attractive to gypsy moths and capture rates in traps baited with PVC-twine lures remain uniform throughout a period of 16 weeks (Leonhardt and others 1992).

Laminated plastic lures, such as Hercon Luretapes®, consist of thin layers of vinyl or other polymers, with synthetic pheromone incorporated into the inner layer at 1.5 to 2.0 percent by weight (Beroza and others 1974). Laminated dispensers also follow first-order loss (McDonough 1978), but we are unaware of published data for the half-life of *E*9-12:OAc or *E9,E*11-12:OAc. In contrast, several commercial lures, such as Consept® membrane lures, Phero Tech® bubble-cap lures, and the Sentry® capillary tube or hollow-fiber lures approximate a zero-order pheromone release. Emission rate for zero-order lures is constant and independent of the concentration of the liquid pheromone (McDonough 1978), but relatively large amounts of neat pheromone are required for these dispensers, which can increase their cost.

Trap catches and degree-day models

NPTM males are present at the start of each generation, before the first females emerge and begin to lay eggs (Berisford and Brady 1972). Sticky traps baited with synthetic pheromone lures are currently deployed in intensively managed plantations of loblolly pines. Pest managers check these traps frequently to determine the beginning of each new generation. When the trap catch equals or exceeds an average of one male NPTM per trap they begin accumulating degree-days for the NPTM temperature/development models (Gargiullo and others 1984; Pickering and others 1989). These models predict the optimum dates for spraying plantations to control NPTM (Gargiullo and others 1983, 1985; Berisford and others 1984; Kudon and others 1988). A model for the coastal plain is also available (Gargiullo and others 1985).

In practice, traps baited with lures containing synthetic NPTM pheromones generally catch high numbers of male moths in infested plantations during the first and second generations, but lower and more variable catches can occur for later generations. This poor response is particularly evident in the coastal plain during the summer months (Gargiullo and others 1985), even when abundant shoot attacks suggest that NPTM populations are high (Asaro and Berisford 2001a). Male flight periods are also less distinct and often overlap for generations 3 and 4 (Gargiullo and others 1985). An alternative technique is to catch first generation NPTM males in traps, then continue accumulating degree days throughout the entire season for predicting the optimum spray dates for all four generations (Gargiullo and others 1985). Unfortunately, these predictions are not as accurate as those using models based upon the onset of each generation and in turn NPTM control is not as good. A method which uses only long-term average temperatures for timing control is also available for seven southern states (Fettig and others 2000).

High efficiency lures and traps are essential for obtaining an accurate date to begin accumulating degree-days for the NPTM models. A standard trap is also needed in order to use pheromone-baited traps for estimating relative population densities. Finally, the successful use of synthetic sex pheromones for NPTM control strategies, such as mating disruption, depend upon a clear understanding of male moth response to synthetic pheromones. The objective of our studies was to investigate some of the factors affecting catches of male NPTM in sticky traps baited with synthetic pheromones and determine promising areas for further research.

MATERIALS AND METHODS

Preparation of Custom Red and Gray Lures

Custom red and gray lures were prepared at the Forestry Sciences Laboratory, Athens, GA. The major component of the NPTM pheromone, *E*9-12:OAc (97.9 percent purity) was purchased from Bedoukin Research Inc., Danbury, CT. The minor component, *E*9,*E*11-12:OAc (88.4 percent purity), was purchased from Chemteck B. V., Amsterdam, The Netherlands. Purity was verified using a Hewlett-Packard GC-MS. The neat synthetic pheromones were stored at - 40 EC until used to formulate pheromone solutions for the custom red and gray septa lures. Red, natural rubber sleeve-type septa, 1.9 by 1 cm (Arthur H. Thomas, Philadelphia, PA) and gray, sleeve-type septa, 1.9 by 1 cm, composed of a halo-butyl isoprene blend elastomer (West Company, Phoenixville, PA) were labeled with a treatment code using a black permanent marking pen.

Stock solutions containing *E*9-12:OAc and *E*9,*E*11-12:OAc in nanograde dichloromethane were prepared and dispensed in 0.1 ml aliquots into the well of each septum. Two additional 0.1 ml aliquots of the solvent were added to each well to insure that any residual pheromone was impregnated into the septa (Brown and McDonough 1986). Loaded septa were allowed to age for 48 hours in a laboratory fume hood (20–24 EC) and then they were wrapped in aluminum foil, placed in labeled glass screw-top bottles, and stored at -40 EC. The first batch of custom gray and red septa lures were prepared on 5 February 1997; a second batch of lures were loaded on 8 May 1997 because we decided to include more tests sites than originally planned. Custom red septa lures from batch 2 were used in tests 6, 9, 11, and 12; custom gray lures from batch 2 were used in tests 6, 11, and 12.

Experimental Design

Each field test was installed in a 2- or 3-year-old loblolly pine plantation with approximately 700 trees per acre. Rows of trees served as a block in a randomized complete block design. Trap positions equal to the number of treatments in the test were established by marking every fifth tree within the row with colored flagging. One row of trees without traps was left between each row of trees with traps. Within each block (row), treatments were randomly assigned to each position. The treatments were rerandomized each time the traps were checked by moving the traps to new positions. Each field test had 5 replicates per treatment, except for the trap design and color tests, which had 6 replicates per treatment.

Trapping Procedure

At each trap position within a test site, a single trap was hung in the tree, near the top, and at approximately the same height (1.0–1.4 m) and cardinal direction relative to the tree stem. The total number of traps used in each test equaled the number of treatments times the number of replicates (blocks). Lures were stored in a freezer and transported to the field in a cooler with ice. Disposable rubber gloves were worn while handling the lures and were changed for each kind of lure. A 1 cm hole was punched in the top of each of the Pherocon 1C traps®, Pherocon CP traps®, Pherocon II traps®, and the Trécé Delta traps® so that a paper clip could be used to suspended a lure from the trap top and prevent it from contacting the sticky trap bottom. New traps and lures were deployed for each test. Traps were checked twice a week at 3–4 day intervals. NPTM caught in the traps were removed and the numbers were recorded on each day the traps were checked.

Commercial and custom NPTM lure tests

Twelve field tests were conducted during 1997–98 to compare commercial and custom NPTM lures. Commercial lures were purchased from Gempler's Inc., Mt. Horeb, WI

and Great Lakes IPM, Vestaburg, MI; each custom red or gray septum lure was loaded with 1 mg of synthetic *E*9-12:OAc and *E*9,*E*11-12:OAc (20:1) as described above. Five to seven of the following treatments were included in each test: 1) Hercon Luretapes® (Hercon Environmental Corp., Emigsville, PA), 2) Scentry® hollow fiber lures, 3) Trécé Red Septa® NPTM lures (Trécé Incorporated, Salinas, CA), 4) Ecogen® Red septa lures (Ecogen Inc., Columbia, MD), 5) Custom Red septa, 6) Custom Gray septa, and 7) Control (unbaited trap). Pherocon 1 C® wing traps (with white plastic top) were used for all treatments. Tests were conducted at sites in Bulloch County, GA; Madison County, GA; Oconee County, GA; Oglethorpe County, GA, Bulloch County, AL, Macon County, AL, Beaufort County, SC; and Southhampton County, VA.

Trap Design Tests

Two field tests were conducted to compare catches of male NPTM in eight commercial traps (fig. 1). Traps were purchased from Gempler's Inc., Mt. Horeb, WI or Great Lakes IPM, Vestaburg, MI. Eight treatments with the following traps were tested: 1) Pherocon 1 C® wing trap (with white plastic top), 2) Pherocon 1C® wing trap (with brown plastic top), 3) Pherocon CP® wing trap (white), 4) Trécé Delta® trap (orange), 5) Trécé Delta® trap (green), 6) Trécé Pherocon II® trap (white), 7) Pherocon Bucket® trap (yellow/white), and 8) Pherocon Bucket® trap (green). Assembly of all traps followed the printed instructions included with the traps. Cattle ear tags containing dichlorvos (DDVP) insecticide (Y-Tex Corporation, Cody, WY) were cut in thirds and one piece was placed in the bottom of each bucket trap to kill the moths caught in the traps. Trécé red rubber septa were used as lures in all of the traps. The tests were conducted from 20 May – 29 June, 1998 in Oglethorpe County, GA and from 15 May – 9 June, 1998 in Bullock County, AL during the emergence of the second generation of NPTM.

Trap Color Tests

Two field tests were conducted to compare catches of male NPTM in Pherocon 1 C® wing traps painted with eight different colors. Treatments included: 1) Red, 2) Yellow, 3) Green, 4) Orange, 5) White, 6) Black, 7) Blue, 8) Gray, and 9) Unpainted (Control). All colors except orange were ColorPlace® fast-drying spray paint (WalMart, Bentonville, AK). Orange paint was not available in that brand so Krylon® interior/exterior spray paint (Sherwin-Williams, Cleveland, OH) was used. The traps were painted one week prior to the tests and left outdoors to allow the paint vapors to dissipate. The first test was conducted from 26 June to 24 July, 1998 in Bullock County, AL. during the emergence of the second NPTM generation. The second test was conducted at the same site from 7 August – 4 September, 1998 during the emergence of the third NPTM generation.

Lure Longevity Test

One field test was conducted to compare the effects of lure longevity on catches of male NPTM in Pherocon 1 C® wing traps. There were three treatments: 1) Trécé Red Septa® NPTM lures replaced weekly, 2) Trécé Red Septa® NPTM lures unchanged, 3) unbaited (Control). The test was conducted in Macon County, AL from 11 July to 8 August, 1997.

Optimum Dosage and Ratio of *E*9-12:OAc : *E*9,*E*11-12:OAc Tests

A field test was conducted to compare the effects of several dosages of *E*9-12:OAc : *E*9,*E*11-12:OAc on catches of male NPTM in Pherocon 1 C® wing traps. Custom Red rubber septa lures were loaded with synthetic NPTM pheromones for six treatments with dosages of *E*9-12:OAc : *E*9,*E*11-12:OAc (20:1) per lure: 1) 2 mg, 2) 1 mg, 3) 0.5 mg, 4) 0.25 mg, 5) 0.125 mg, and 6) unbaited trap (Control). The test was conducted in Oconee County, GA 20 March to 5 May, 1997.

A second test was conducted to compare the effects of *E*9-12:OAc : *E*9,*E*11-12:OAc ratios on catches of male NPTM in Pherocon 1 C® wing traps. Custom Red rubber septa lures were loaded with 1 mg of synthetic NPTM pheromones for six treatments with ratios of *E*9-12:OAc : *E*9,*E*11-12:OAc: 1) 5:1, 2) 10:1, 3) 20:1, 4) 40:1, 5) 80:1, and 6) unbaited trap (Control). The test was conducted in Oconee, GA 20 March to 5 May, 1997.

Data analyses

Treatment means and standard errors (± SE) were calculated for each test. Trap catches of male NPTM were transformed by $\log_e (x + 1)$ to meet the assumptions of analysis of variance (ANOVA) and analyzed using PROC GLM for randomized complete block designs, followed by the Tukey test at " = 0.05 (SAS Institute 1990).

RESULTS

There were significant differences ($F_{44,248} = 5.59$, $P = 0.0001$) in catches of NPTM among rows (blocks) within each of the 12 Lure tests. In all of our field tests, traps in the two outer rows of trees generally caught more moths than traps placed in trees located in interior rows.

Commercial and custom NPTM lure tests

There were significant differences in trap catches among traps baited with the various lures treatments in 10 of our 12 Lure tests (fig. 2–5): Test # 1 $F = 3.48$, $P = 0.0315$; Test # 2 $F = 1.26$, $P = 0.3213$; Test # 3 $F = 4.68$, $P = 0.0108$; Test # 4 $F = 4.89$, $P = 0.0090$; Test # 5 $F = 1.82$, $P = 0.1547$; Test # 6 $F = 12.96$, $P = 0.0001$; Test # 7 $F = 5.59$, $P = 0.0022$; Test # 8 $F = 7.67$, $P = 0.0004$; Test # 9 $F = 10.02$, $P = 0.0001$; Test # 10 $F = 10.88$, $P = 0.0.0002$; Test # 11 $F = 9.10$, $P = 0.0001$; and Test # 12 $F = 5.46$, $P = 0.0025$.

In nine of the tests, control traps without lures caught few moths, but mean catches per trap were 10.8 ± 2.1 for generation 1 (Test #9) in Alabama, and 10.6 ± 2.6 for generation 1 (Test #10) and 23.6 ± 10.9 generation 2 (Test #11) in Virginia. NPTM populations were very high during these three tests and trap catches for the best lures in each test were 9 to 28 times those for the control traps.

No single lure was best in all locations and generations and there was a significant treatment by location interaction ($F_{56,248} = 8.50$, $P = 0.0001$). Traps with the Trécé® red septa lures, Ecogen® red septa lures, and Sentry® fiber lures caught significantly higher numbers of moths than the Hercon luretapes® (figs. 2–5). Custom red and gray septa lures from batch 1 performed well (figs. 2–5), and catches in

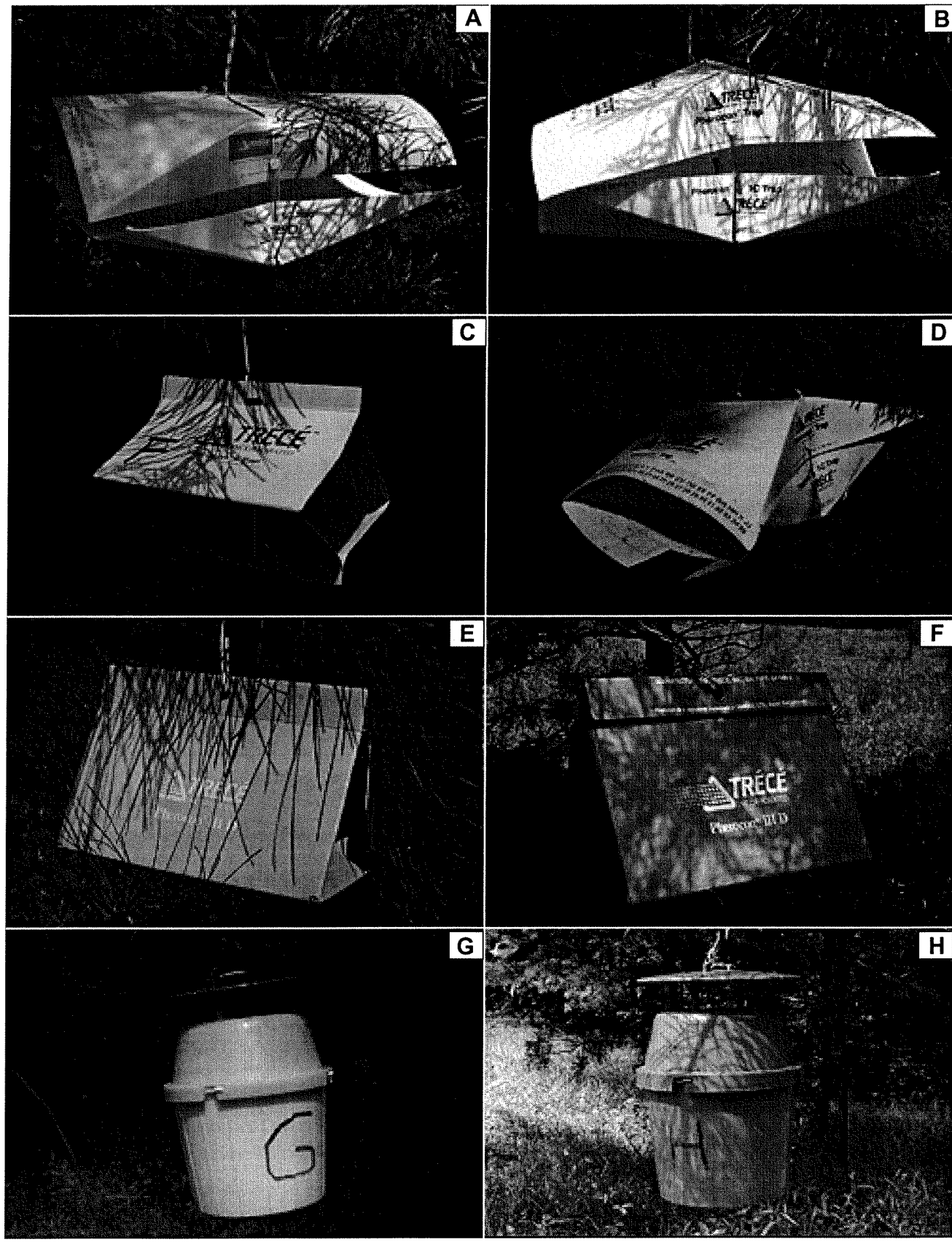

Figure 1—Commercial traps used in the trap design tests: (A) Pherocon 1 C® wing trap (with brown plastic top), (B) Pherocon 1C® wing trap (with white plastic top), (C) Trécé Pherocon II® trap (white), (D) Pherocon CP® wing trap (white), (E) Trécé Delta® trap (green), (F) Trécé Delta® trap (orange) (G) Pherocon Bucket® trap (yellow/white), and (H) Pherocon Bucket® trap (green).

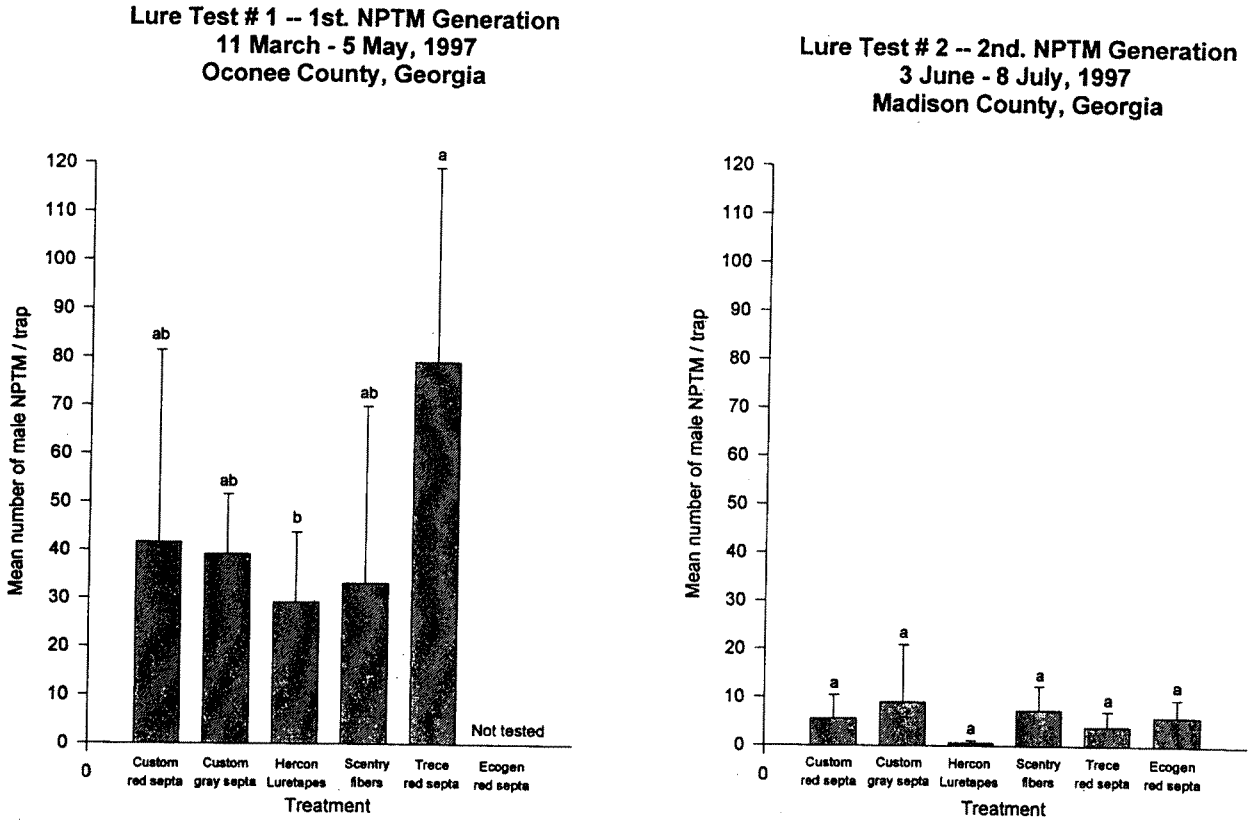

Figure 2—Catches of NPTM males in Pherocon 1C® wing traps baited with custom and commercial lures, Georgia Piedmont, 1997.

traps with the three best commercial baits were generally not significantly different from the batch 1 custom lures. Custom lures from batch 2 performed poorly in all tests where they were used (custom red septa lures, tests 6, 9, 11, and 12 and custom gray, tests 6, 11, and 12), apparently because these septa were improperly loaded.

Trap Design Tests

Catches differed significantly among treatments in Trap Design Test # 1 (F = 15.26, P = 0.0001) and Trap Design Test # 2 (F = 16.73, P = 0.0001). Pherocon wing traps®, with either the white or brown top, captured significantly more moths than the other traps tested in both tests (fig. 6). The Pherocon II® trap captured only about half as many moths as wing traps. Other traps tested were less effective and caught significantly fewer moths than the wing traps. The poorest traps were the orange and green Trécé Delta Traps®, and the Pherocon Green Bucket® trap. These traps were also late in predicting first male NPTM catches in both tests (table 1).

Trap Color Tests

Catches differed significantly among treatments in Color Test # 1 (F = 4.86, P = 0.0003) and Color Test # 2 (F = 3.94, P = 0.0016). Pherocon 1 C® wing traps painted red, yellow, blue or gray caught significantly fewer moths than unpainted traps in Color Test #1, but only blue or gray traps had lower catches in Color Test # 2 (fig. 7). Unpainted Pherocon 1 C® wing traps consistently caught more moths than painted traps. Gray traps had the lowest catches.

Lure Longevity Test

Catches of NPTM males in Pherocon 1 C® wing traps with Trécé Red rubber NPTM lures were replaced weekly did not differ significantly (F = 2.2, P = 0.2049) from those for traps where the lures were not changed (fig. 8). Differences in the mean number of NPTM males caught per trap between treatments, within each trapping period were similar and the treatment by trapping period interaction was not significant (F = 0.0, P =0.947).

Optimum Dosage and Ratio of *E*9-12:OAc : *E*9,*E*11-12:OAc Test

Catches of NPTM males in Pherocon 1 C® wing traps differed significantly among treatments (F = 3.30, P = 0.020) with red rubber septa lures containing different dosages of *E*9-12:OAc : *E*9,*E*11-12:OAc (20:1). The treatment by trapping period interaction was not significant (F = 0.91, P = 0.637). Traps with the 0.125mg lures caught significantly more moths than traps without lures or with 1mg lures (fig. 9). There was no significant difference among catches for traps with 0.125, 0.25, 0.5, or 2 mg lures.

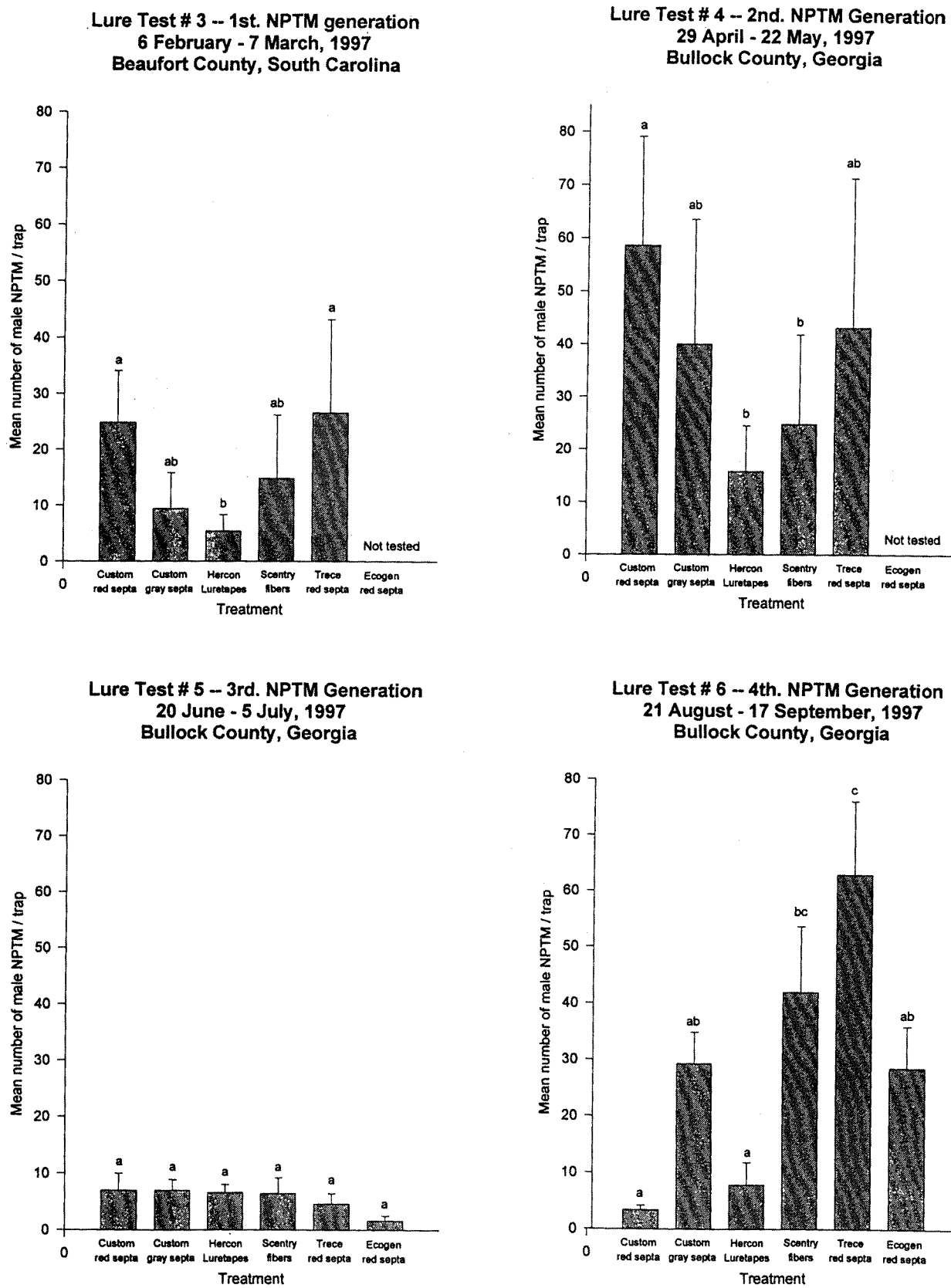

Figure 3—Catches of NPTM males in Pherocon 1C® wing traps baited with custom and commercial lures, South Carolina and Georgia Coastal Plain, 1997.

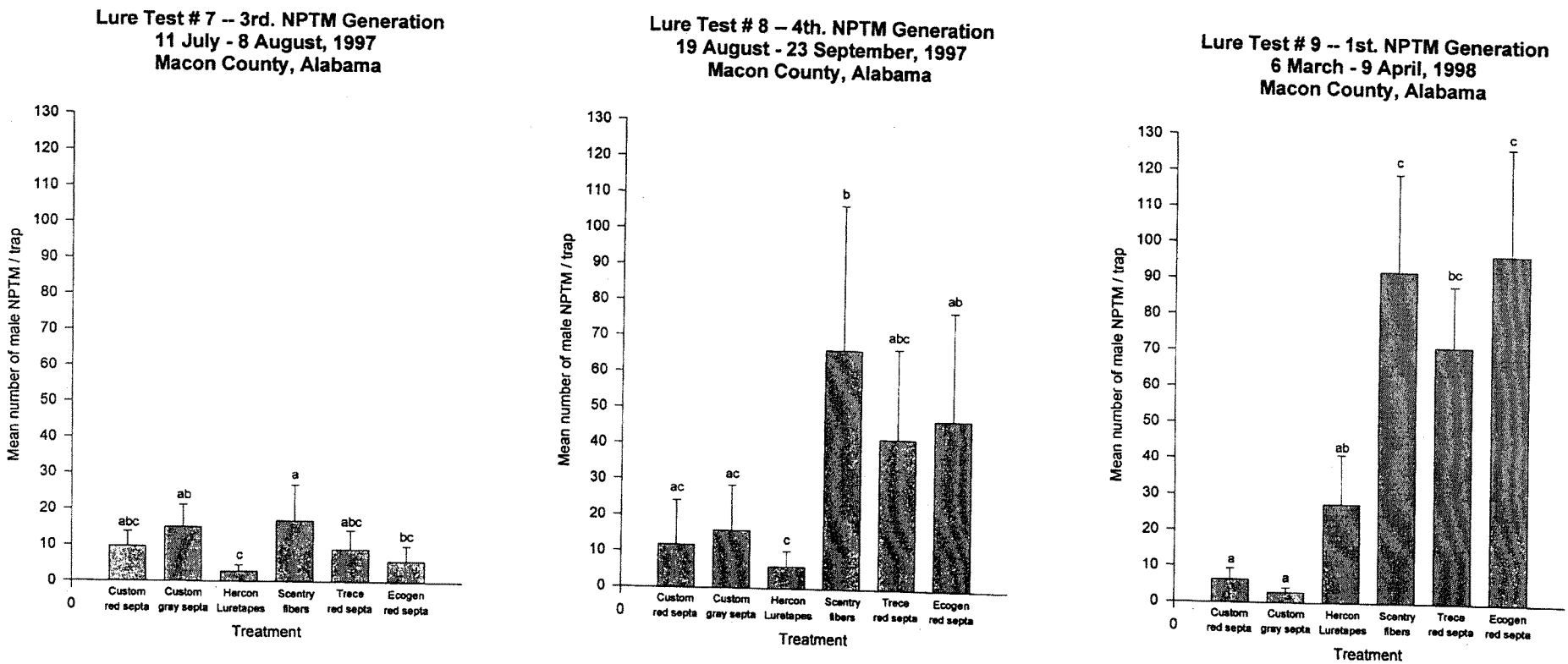

Figure 4—Catches of NPTM males in Pherocon 1C® wing traps baited with custom and commercial lures, southeastern Alabama, 1997–1998.

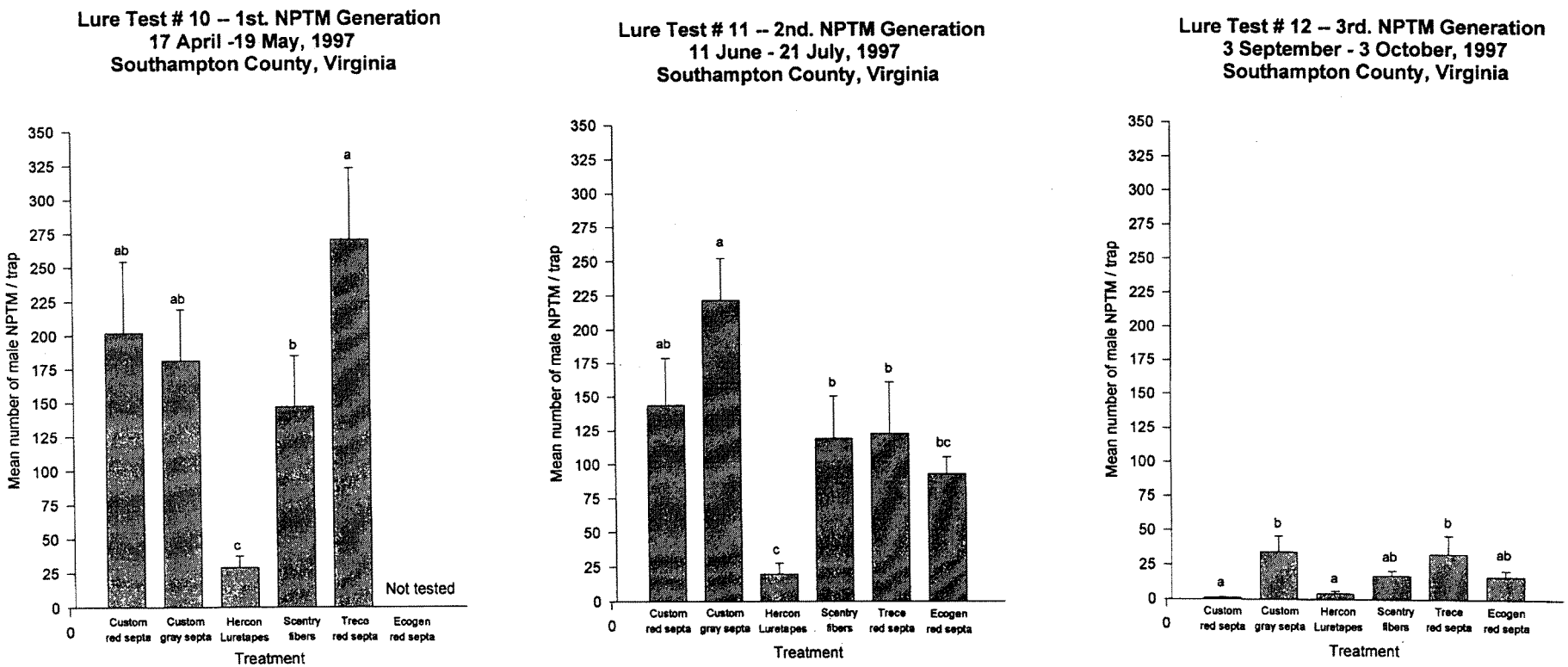

Figure 5—Catches of NPTM males in Pherocon 1C® wing traps baited with custom and commercial lures, southeastern Virginia, 1997.

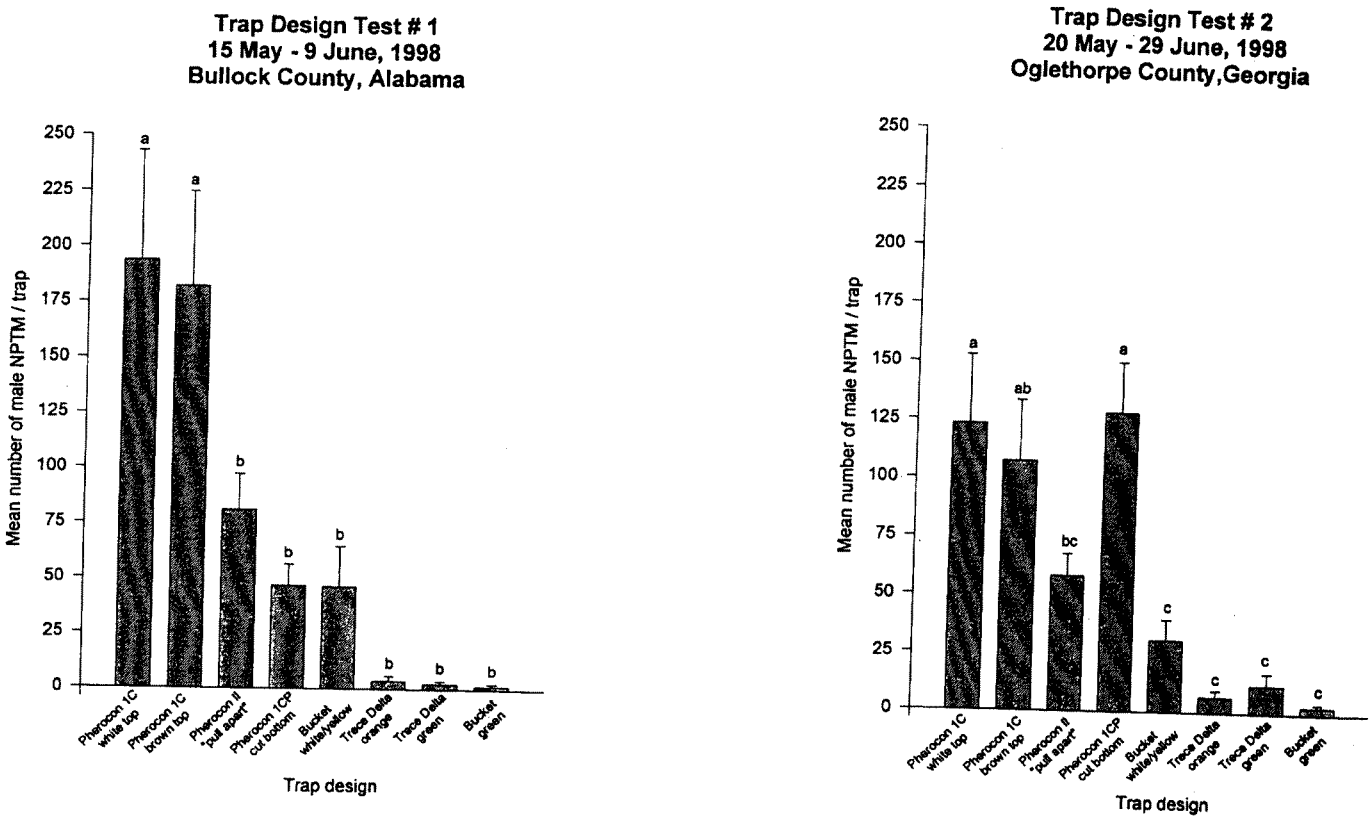

Figure 6—Catches of NPTM males in eight commercial traps baited with Trécé red rubber septa lures, Alabama and Georgia, 1998.

Table 1—Dates for first male NPTM catches ● and dates on which catch equaled or exceeded an average of 1 moth/trap ✱ for eight types of traps baited with Trece red rubber lures, 1998

	Test # 1 — Alabama			Test #2 — Georgia				
Trap type	5/15[a]	5/19	5/22	5/26	5/29	6/01	6/04	6/08
Pherocon 1C - White	● ✱	—	—	● ✱	—	—	—	—
Pherocon 1C - Brown	● ✱	—	—	● ✱	—	—	—	—
Pherocon II	● ✱	—	—	● ✱	—	—	—	—
Pherocon 1CP	● ✱	—	—	● ✱	—	—	—	—
Delta - Green	—	● ✱	—	●	✱	—	—	—
Delta - Orange	—	—	● ✱	● ✱	—	—	—	—
Bucket- White/yellow	● ✱	—	—	●	✱	—	—	—
Bucket - Green	—	● ✱	—	—	●	—	—	✱

[a] Traps checked for moths at 3–4 day intervals.

Catches of NPTM males in Pherocon 1 C® wing traps differed significantly among treatments ($F = 3.24$, $P = 0.0138$) with red rubber septa lures containing different ratios of *E*9-12:OAc : *E*9,*E*11-12:OAc. The treatment by trapping period interaction was significant ($F = 1.64$, $P = 0.0216$), but too few moths were caught during each trapping period to examine the relative lure effectiveness over time. Traps with lures containing pheromone ratios of 1:5, 1:10, and 1:20 caught the highest number of moths and did not differ significantly from each other (fig. 9).

DISCUSSION AND CONCLUSIONS

Our tests results have important implications for NPTM pest management. They show that not all NPTM lures or traps

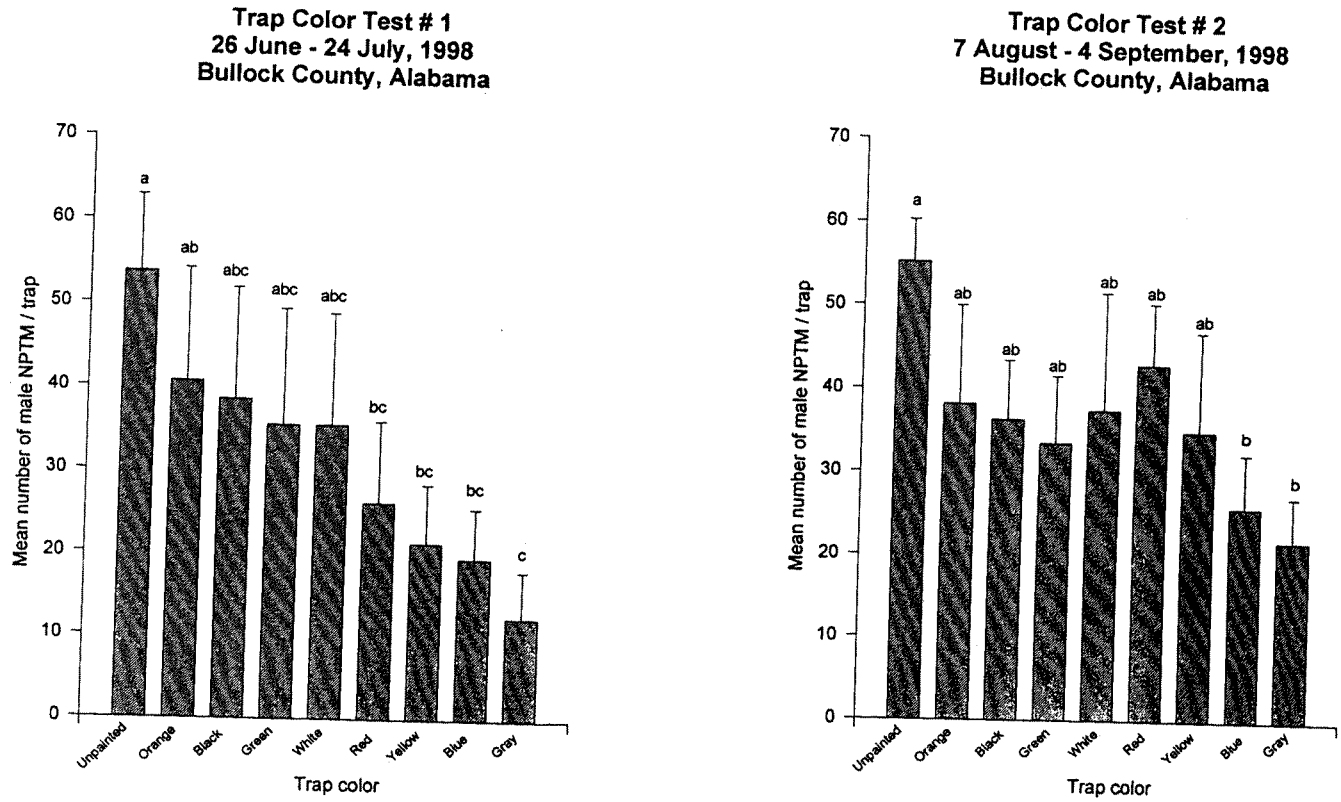

Figure 7—Catches of NPTM males in Pherocon 1C® wing traps painted eight colors and baited with Trécé red rubber septa lures, Alabama, 1998.

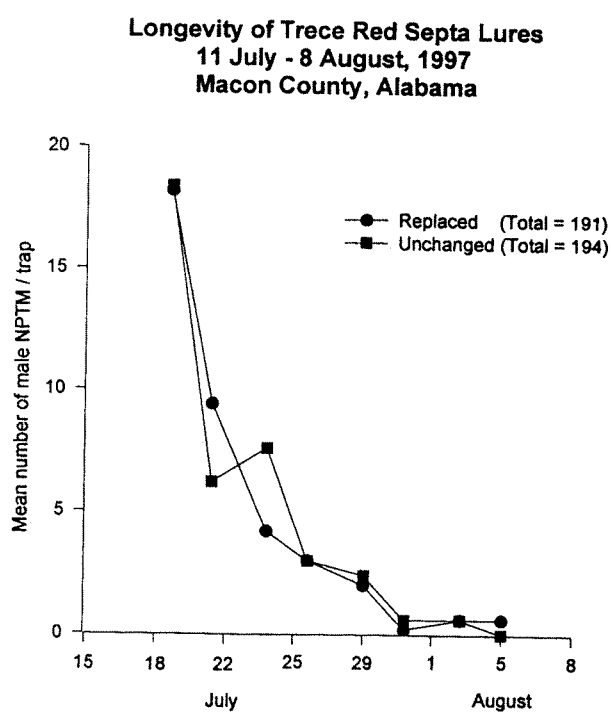

Figure 8—Catches of NPTM males in Pherocon 1C® wing traps baited with Trécé red rubber septa lures changed weekly or unchanged, Alabama, 1998.

are equally effective in attracting male moths. Three important factors which affect the performance of NPTM lures include lure type, dosage, and the *E*9-12:OAc : *E9,E*11-12:OAc ratio. Several possible scenarios involving these factors may explain the differences in lure performance and poor summer efficiency of the NPTM traps.

First, both NPTM pheromone components may volatilize and dissipate because of the high ambient temperatures, causing the lures to quickly lose their effectiveness. Lures with higher dosages may be needed during the hot summer and fall months, than in the cooler spring months.

Second, high ambient temperatures in the summer may increase the loss of *E*9-12:OAc on NPTM lures to a rate high enough to inhibit NPTM males. Traps baited with 1 mg of *Z*11-16:OAc lures catch only half as many southern pine coneworm, *D. amatella* moths, as lures with 0.3 or 0.1 mg (Meyer and others 1986).

Third, summer temperatures may cause *E,E*-9,11-12:OAc to rapidly dissipate or degrade, changing the optimum ratio of the two components and eventually leaving only the major compound. Without the minor component, *E*9-12:OAc alone is a weak attractant (Hill and others 1981). Exposure to UV light during the long summer days may also cause isomerization of the diene, *E,E*-9,11-12:OAc, to an inactive isomer, changing the 95:5 ratio of the pheromones. Rapid isomerization of conjugated dienes occurs on red natural rubber septa lures, but it is minimal on gray butyl rubber septa (Brown and McDonough 1986).

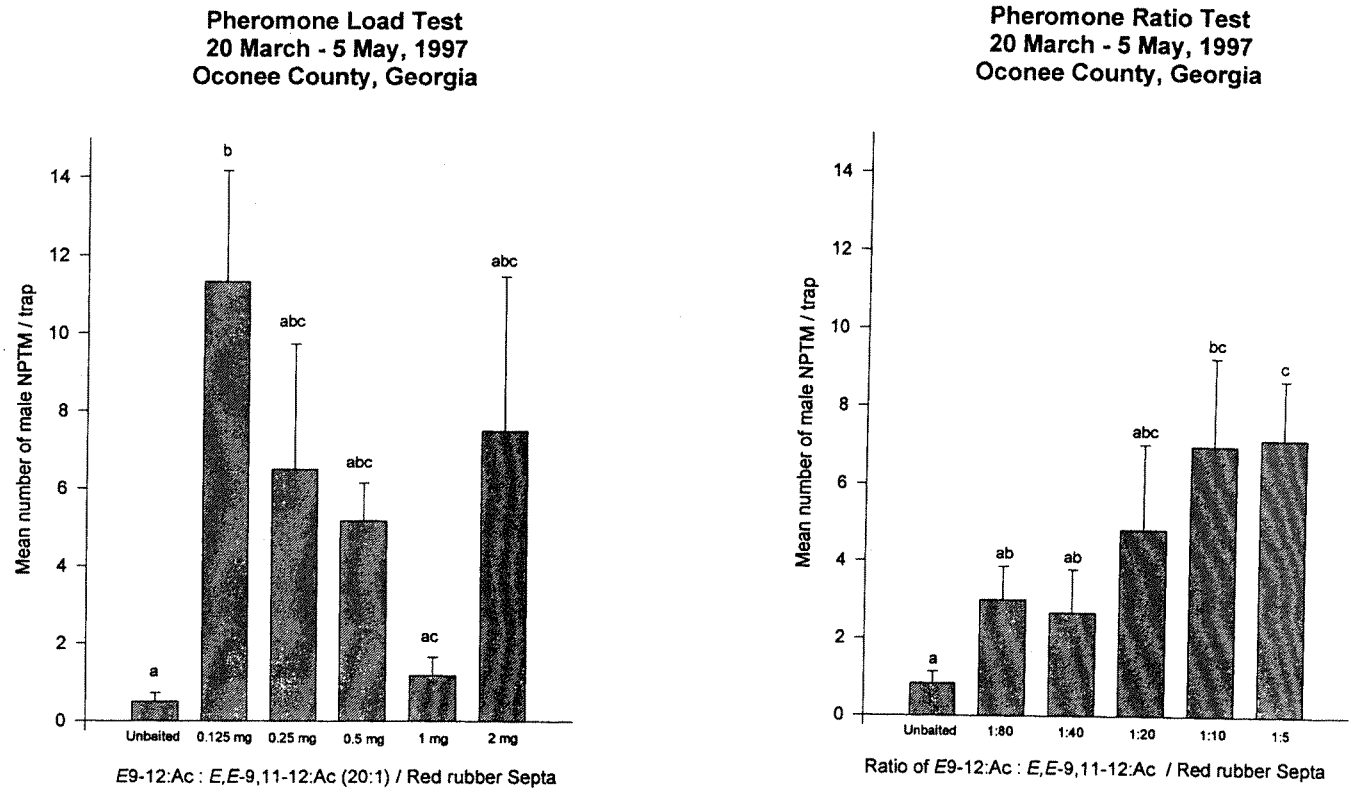

Figure 9—Catches of NPTM males in Pherocon 1C® wing traps baited with custom gray rubber septa lures loaded with different amounts or ratios of pheromones, Georgia, 1997.

Fourth, the optimum ratio of the two synthetic NPTM pheromone components for attracting males may change during the summer months. For example, the omnivorous leafroller moth, *Playnota stultan* (Walsingham), produces the same ratio of its two-component pheromone during three flight periods in May, August and October, but the best pheromone component ratios in lures change for each generation (Baker and others 1978).

Finally, if trap catches of NPTM are low because males have a shorter life span (Asaro and Berisford 2001b) or are less responsive during the summer months than in the spring or because the lures are not competitive with high numbers of feral females, it may be impossible to develop a "better lure" for hot weather conditions.

The traps we tested varied in both the size of the opening through which the moths entered the trap and the area of sticky trap surface. For example, the Pherocon Delta traps® have a smaller opening and less sticky surface than any of the other cardboard sticky traps we tested. In addition, we closed the end panels as indicated in the instructions provided with the trap. Delta traps with the end panels fully open, should be tested again to compare their performance with wing traps. Although trap color influenced trap catch, it may not be as important for NPTM males as for some other insects and commercially available white wing traps appear suitable for NPTM.

Traps or lures with poor efficacy will mislead forest managers or Christmas tree growers about the onset of moth flight and moth population levels. Using the most effective pheromone lure is extremely important when traps are used to detect the first NPTM moths for initiating degree-day models for predicting optimum spray dates. When traps are used to monitor tip moth populations and predict the need for control, consistent performance of lures and traps will be even more important and it will be necessary to adopt a standard lure and trap combination. Our studies suggest that further research to develop a more effective and reliable lure may be warranted.

ACKNOWLEDGMENTS

We extend our special thanks to Marc Davidson and Jimmy Seckinger, International Paper Company; Kason Furnas, Department of Horticulture, Auburn University; and Chris Crowe and Mike Cody, Southern Research Station, USDA Forest Service for locating the study sites, installing the tests and monitoring the traps. Mark Dalusky, Department of Entomology, University of Georgia provided helpful suggestions. We thank Dan Miller, Southern Research Station, for reviewing the manuscript. International Paper Company (formerly Union Camp Corporation) and Champion Paper Company allowed us access to their pine plantations. Funding was provided by the Union Camp Corporation, the USDA Forest Service Southern Research Station, and the University of Georgia-Industry Pine Tip Moth Research Consortium.

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The Nantucket pine tip moth, *Rhyacionia frustrana* (Comstock) has become a more prevalent pest in the South as pine plantation management has intensified. The Pine Tip Moth Research Consortium was formed in 1995 to increase basic knowledge about the moth and to explore ways to reduce damage. A conference was held in 1999 at the Entomological Society of America annual meeting in Atlanta, GA, to review some recent research on the moth. Papers presented at the conference included work on damage assessment (impact) and a review of previous attempts to quantify tip moth damage, interactions of the moth with different forest management practices and the relationship with intensive management, effects of herbicide and insecticide use on tip moth parasitoids, evaluations of different types of insecticides for tip moth control, methods for optimizing chemical control through more precise timing, potential for augmenting tip moth egg parasites by releases of laboratory-reared parasitic wasps, a review of the potential opportunities for using pheromone traps to predict tip moth infestation density and damage and evaluations of different pheromone trap designs and lures.

Keywords: Biological control, chemical control, forest management, growth impact, pheromone traps, pine tip moth, *Pinus taeda*, *Rhyacionia frustrana*.

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