

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

Christopher Asaro and C. Wayne Berisford¹

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) (Lathief 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.

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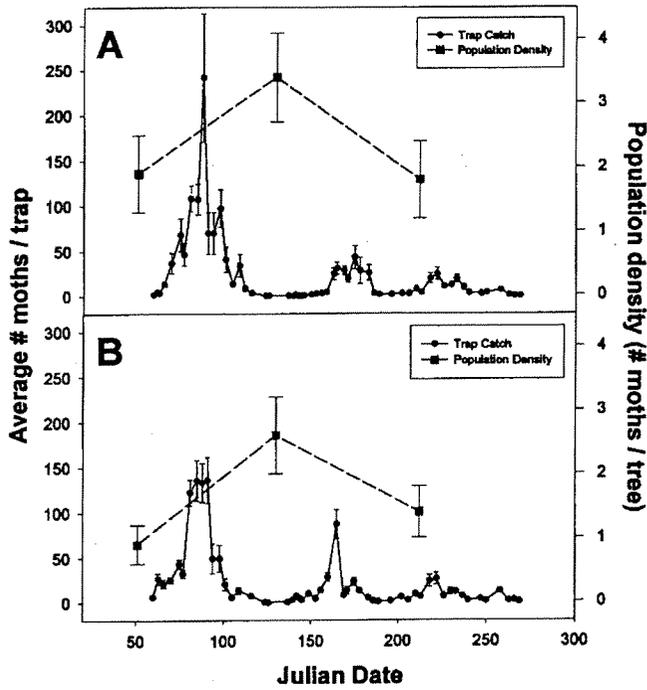


Figure 1—Average number (\pm SE) of *R. frustrana* males caught in traps and the associated populations density prior to adult emergence from February through September, 1997 at two sites in Clarke and Morgan counties, Georgia A) Harve Mathis Road and B) Bostwick.

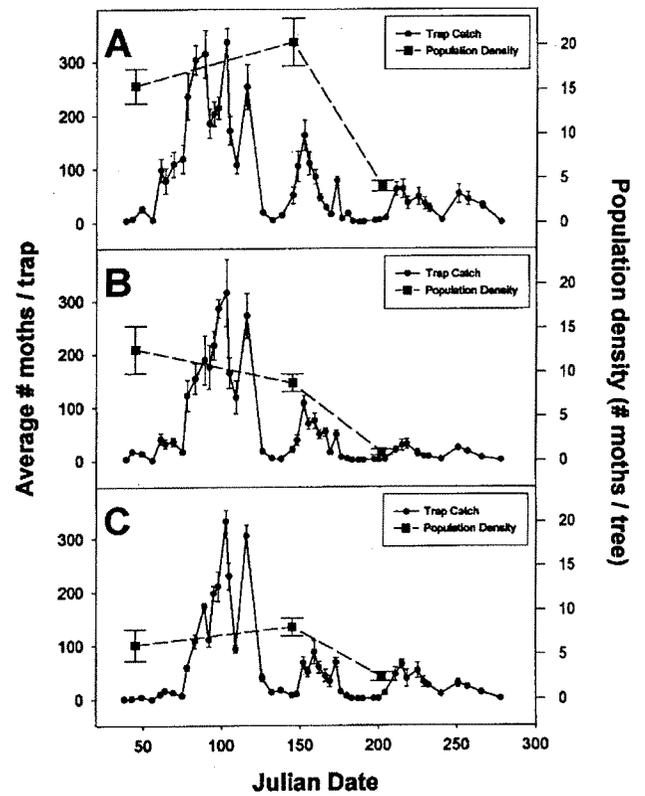


Figure 3—Average number (\pm SE) of *R. frustrana* males caught in traps and the associated populations density prior to adult emergence from February through September, 1999 at three sites in Oglethorpe county, Georgia A) Lexington, B) Maxeys and C) Arnoldsville.

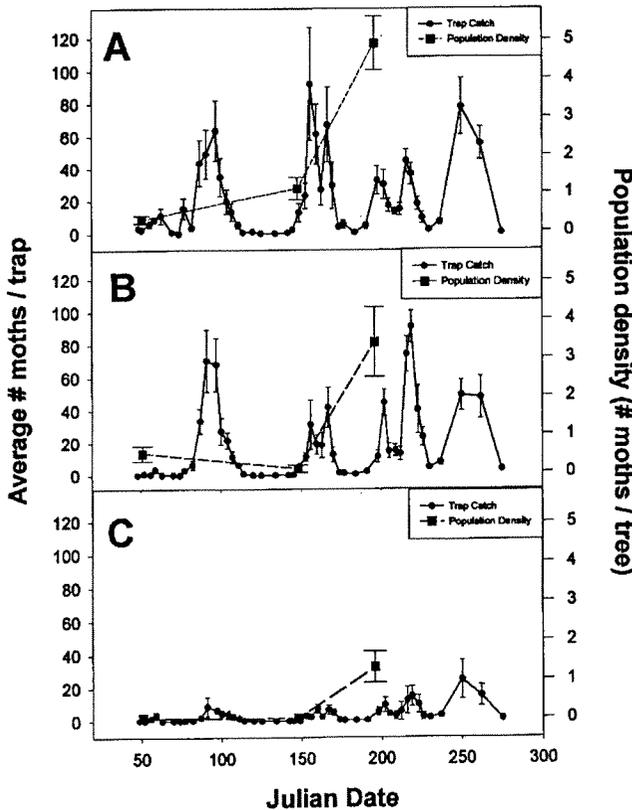


Figure 2—Average number (\pm SE) of *R. frustrana* males caught in traps and the associated populations density prior to adult emergence from February through September, 1998 at three sites in Oglethorpe county, Georgia A) Lexington, B) Maxeys and C) Arnoldsville.

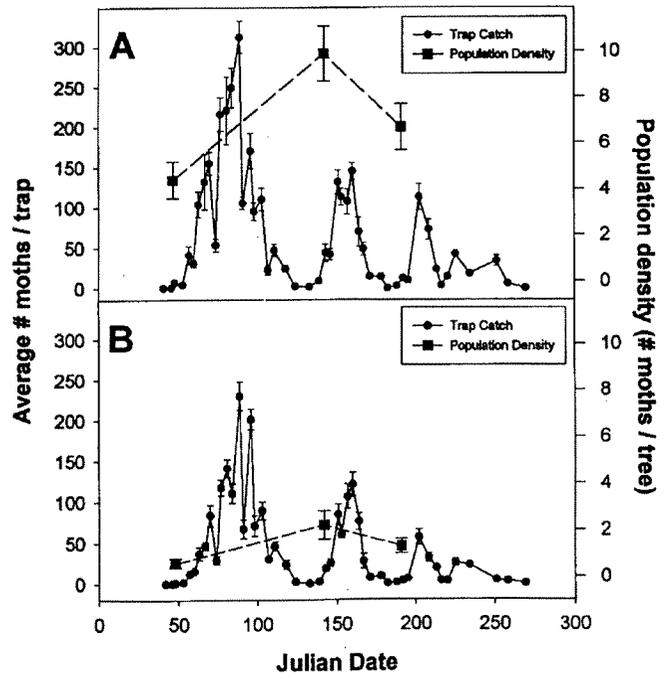


Figure 4—Average number (\pm SE) of *R. frustrana* males caught in traps and the associated populations density prior to adult emergence from February through September, 2000 at two sites in Oglethorpe county, Georgia A) Lexington and B) Wilkes Farm.

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 $\alpha=0.05$.

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 (\pm 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 (\pm 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

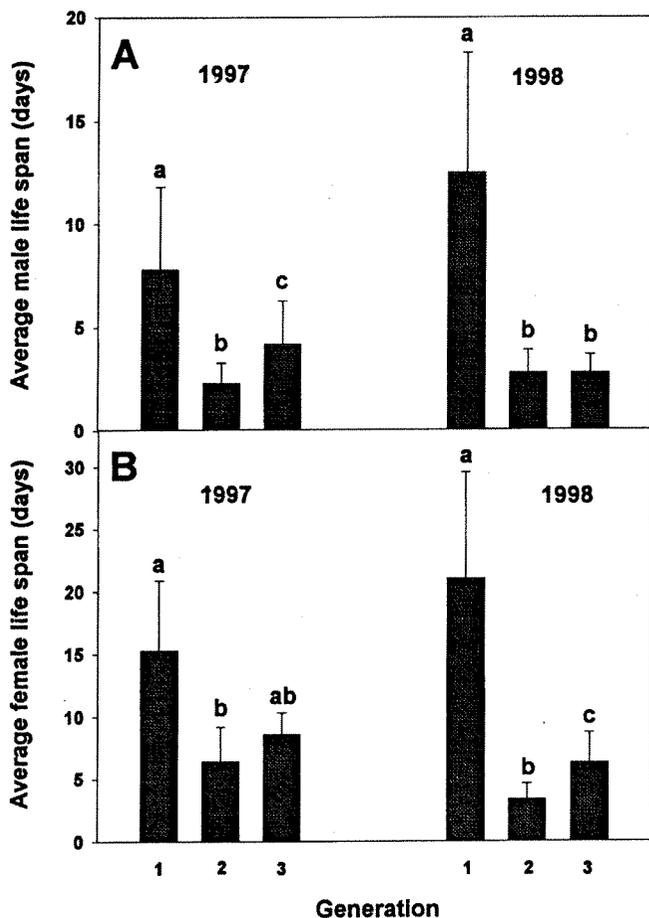


Figure 5—Average (\pm SD) life span of each generation of adult *R. frustrana* males (A) and females (B) in a loblolly pine plantation near Athens, Georgia during 1997 and 1998. Within each year, means followed by the same letter are not significantly different at $\alpha=0.05$ (Dunn's Method).

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

Average (\pm SD) daily temperature and humidity during the 1997 field experiment was 15.1°C (\pm 2.8) and 57.0 percent (\pm 16.7), respectively, for first generation moths (March 18 to April 11), 26.1°C (\pm 1.5) and 74.8 percent (\pm 5.7) for second generation moths (June 19 to July 6), and 25°C (\pm 2.7) and 64.5 percent (\pm 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 (\pm 4.7) and 69.5 percent (\pm 17.0) for the first generation (February 28 to May 4), 25°C (\pm 3.0) and 66.2 percent (\pm 9.2) for the second generation (June 4 to June 16), and 26.6°C (\pm 1.7) and 64.0 percent (\pm 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 (\pm SD) at 5, 10, 20, 30, 35, and 40°C treatments was 8.2 (\pm 3.1) ($n=15$ males), 7.9 (\pm 3.2) ($n=22$), 4.4 (\pm 2.4) ($n=29$), 1.5 (\pm 0.7) ($n=20$), 1.0 (\pm 0.3) ($n=41$), and 0.7 (\pm 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 (\pm SD) at 5, 15, 25, 30, and 35°C treatments was 10.8 (\pm 1.9) ($n=15$ males), 4.3 (\pm 1.4) ($n=20$), 2.4 (\pm 0.8) ($n=10$), 2.6 (\pm 1.1) ($n=9$), and 1.6 (\pm 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 (\pm 1.4) days, those in the wet cotton treatment lived 4.0 (\pm 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, $\alpha = 0.05$.

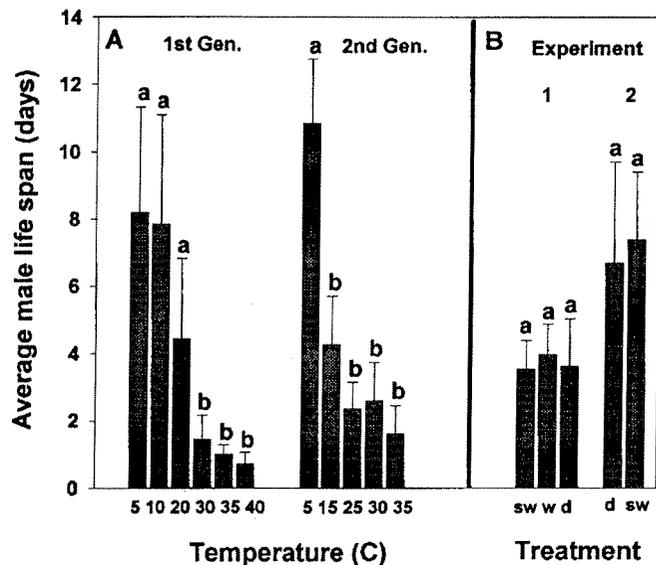


Figure 6—(A) Average (\pm SD) life span of adult *R. frustrana* males under different constant temperatures using moths from the first and second generations and (B) two experiments comparing male moth life span under different treatments (sw=sugar water, w=water only, d=dry) and constant temperatures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

(\pm 0.8) days. In Experiment 2, moths in the dry cotton treatment lived 6.7 (\pm 3.0) days while those in the sugar water treatment lived 7.4 (\pm 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 (\pm SE) ratio of total trap catch to population density (number of moths per tree) was 707 (\pm 216) for the first adult emergence peak, 114 (\pm 33) for the second peak, and 97 (\pm 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,

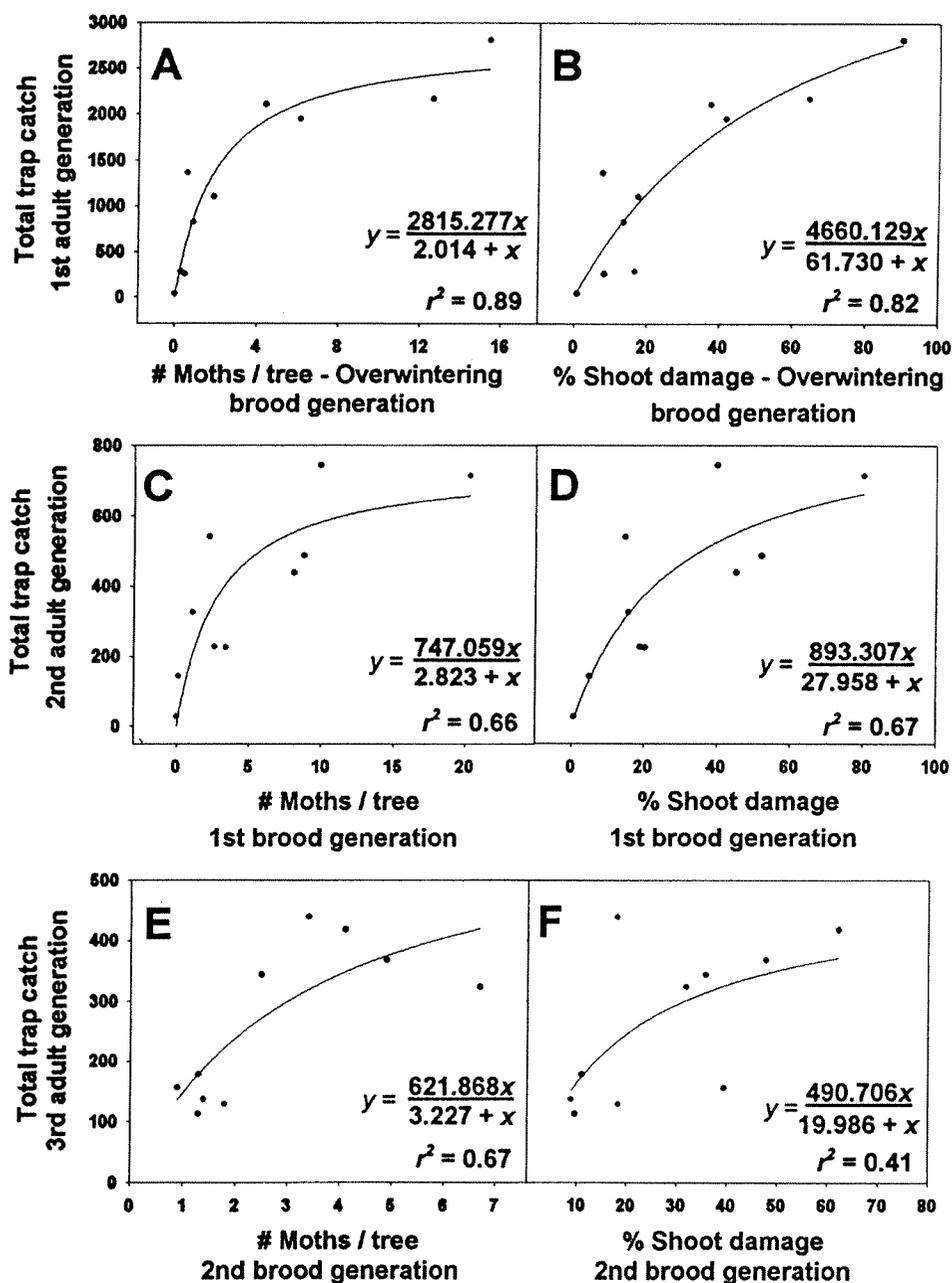


Figure 7—Regression analyses modeling the relationship between A) *R. frustrana* overwintering brood population density and total trap catch during the first adult generation, B) average percent shoot infestation of the overwintering brood and total trap catch during the first adult generation, C) *R. 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, Lexington) 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

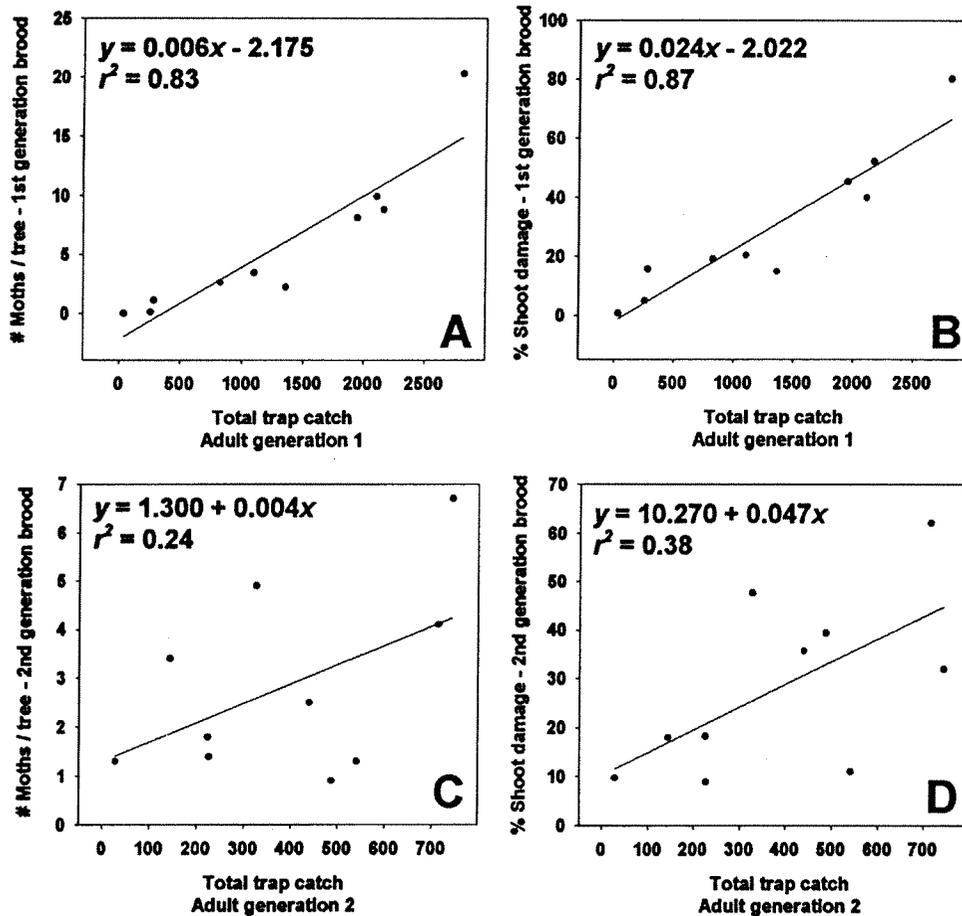


Figure 8—Regression analyses modeling the relationship between A) total trap catch during the first adult generation and *R. frustrana* population density during the first generation brood, B) total trap catch during the first adult generation and average percent shoot infestation during the second generation 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 (\pm SD) percentage of total moths caught prior to the spray date was 65.3 percent (\pm 14.6) for the first adult generation, 85.1 percent (\pm 6.7) for the second adult generation, and 47.9 percent (\pm 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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