Predicting Infestation Levels of the Nantucket Pine Tip Moth (Lepidoptera: Tortricidae) Using Pheromone Traps

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ABSTRACT There is considerable interest in using pheromone trap catches of the Nantucket pine tip moth, *Rhyacionia frustrana* (Comstock), to estimate or predict population density and damage. At six sites in the Georgia Piedmont, adult tip moths were monitored through one or more years using pheromone traps while population density and damage for each tip moth generation were determined. During most years, trap catch was higher during the first adult generation compared with subsequent generations regardless of population density. Within each generation, trap catch was moderately to highly correlated with associated population density or damage levels. Hyperbolic regression models best described these relationships and suggested trap saturation when populations are high. Trap catch during the first adult generation was highly predictive of population density or damage during the subsequent generation. Trap catch during the second adult generation was fair at predicting subsequent density or damage. The models presented herein should be used with caution because they are likely to be region-specific. Validation of these relationships is necessary before widespread application of these models is warranted.

KEY WORDS *Rhyacionia frustrana*, *Pinus taeda*, pheromone traps, population density, host damage, prediction

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THE NANTUCKET PINE tip moth, *Rhyacionia frustrana* (Comstock), can be a significant pest of commercially important southern pine seedlings and saplings (Berisford 1988). The female produces a two-component sex pheromone identified by Hill et al. (1981). Traps baited with crude pheromone extracts or synthetic pheromone have been used to monitor seasonal activity (Berisford 1974, Canalos and Berisford 1981), daily activity, and behavior of male moths (Berisford and Brady 1972, 1973; Berisford et al. 1974; Berisford 1977; Webb and Berisford 1978), and for the application of spray-timing models (Berisford et al. 1984; Gargiullo et al. 1984, 1985; Fettig et al. 2000a). There has been long-term interest in the use of pheromone traps to predict tip moth density or host damage. However, the extent to which seasonal trap catches for this multivoltine insect are positively correlated with population levels has not been documented.

Some studies that attempted to positively correlate trap catch with insect population density or host damage have met with failure (Miller and McDougall 1973, Howell 1974, Srivastava et al. 1992). One hypothesis frequently cited to explain this failure 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, there are studies on some important forest pests in which some measure of population density or host damage has been positively correlated with pheromone trap catch, including the Douglas-fir tussock moth, *Orgyia pseudotsugata* (McDunnough) (Daterman et al. 1979), spruce budworm, *Choristoneura fumiferana* (Clemens) (Allen et al. 1986), and gypsy moth, *Lymantria dispar* (L.) (Gage et al. 1990, Thorpe et al. 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 et al. 1993, Drapek et al. 1997). Given the importance of the Nantucket pine tip moth to intensive forest management (Ross and Berisford 1990, Ross et al. 1990, Nowak and Berisford 2000), a more sophisticated monitoring system for this pest involving pheromone traps is desirable.

Adult tip moths oviposit on needles and shoots of the host tree. Upon hatching, first-instar larvae mine needles. Second instar larvae feed at needle or bud axils, forming a characteristic silk tent covered with resin. Subsequent instars (3–5) feed inside buds and shoots and ultimately pupate inside the dead shoot, where they overwinter in the last annual generation. (Berisford 1988). Peak emergence for the first adult population typically occurs from mid-January to early April depending on latitude and elevation. A lower threshold temperature of 9.5°C is required for egg development and activity of all life stages, including adult flight, whereas 40°C is the upper threshold tem-

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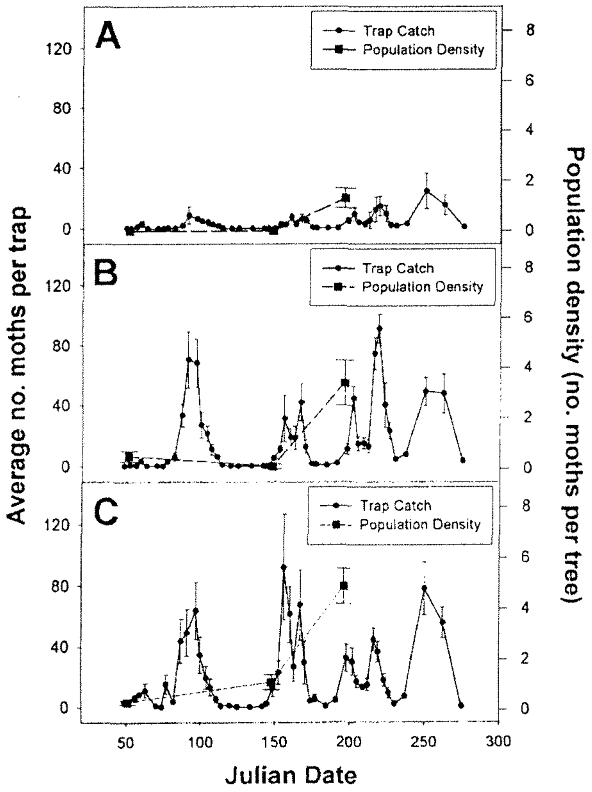

Fig. 2. Average number (±SE) of *R. frustrana* males caught in traps and the associated population density (±SE) before adult emergence from February through October 1998 at three sites in Oglethorpe County, GA. (A) Arnoldsville. (B) Maxeys. (C) Lexington.

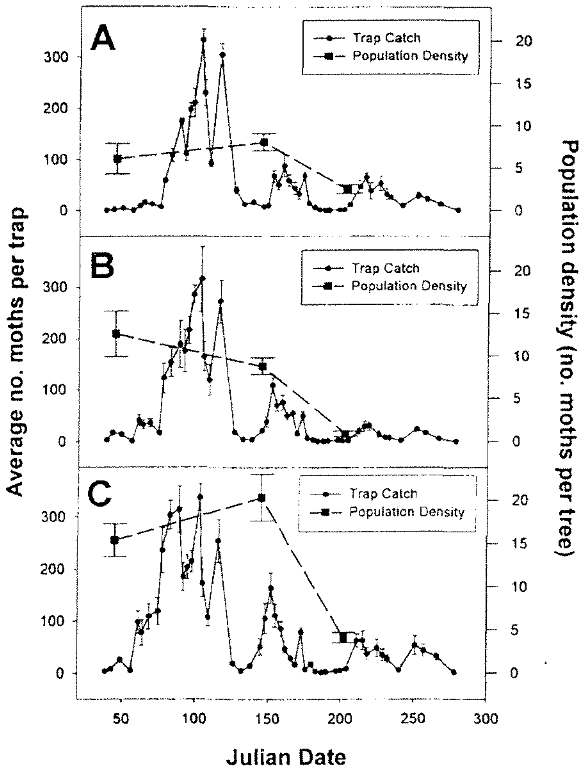

Fig. 3. Average number (±SE) of *R. frustrana* males caught in traps and the associated population density (±SE) before adult emergence from February through October 1999 at three sites in Oglethorpe County, GA. (A) Arnoldsville. (B) Maxeys. (C) Lexington.

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 before adult emergence that did not include larvae.

In addition to estimates of population density, whole tree damage estimates were also obtained from each site before 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 nonlinear regression models using Sigmaplot 4.01 (SPSS 1997). Scatter plots were examined before 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 at most sites, particularly between the overwintering and first generation broods (Figs. 1A and B, 3A and C, and 4A and B). This pattern was not evident in 1998, however, when populations were similar during the first two generations and increased substantially during the third generation. Populations were low overall in 1998 (Fig. 2). In one case, the second trap catch peak was slightly greater than the first, spring peak (Fig. 2C), but there was an almost four-fold population increase during this period (Table 1). 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

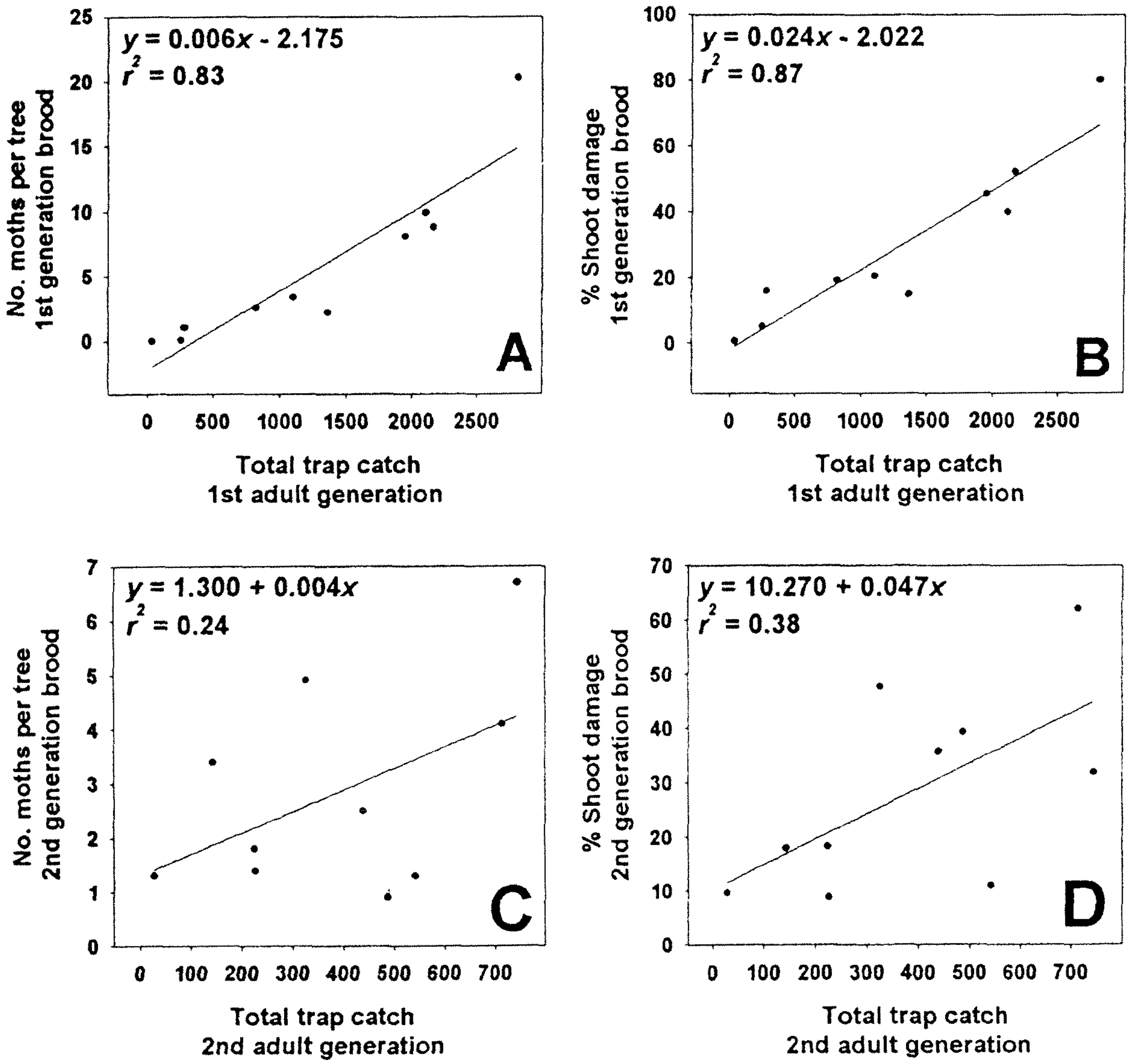

Fig. 6. Regression analyses modeling the relationship between (A) total trap catch during the first adult generation and *R. frustrana* population density during the first generation brood, (B) total trap catch during the first adult generation and average percent shoot infestation during the first generation 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.

study. Increased competition from calling females may also cause trap catch to level off at high densities (Knipling 1979, Unnithan and Saxena 1991).

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. 5F); two outlying points cause this regression to be substantially poorer than the associated regression using tip moth density (Fig. 5E). One of these outliers (the Maxeys 2 site) had 89% tip moth mortality within the damaged shoots during the third generation (Table 1). This produced an overestimate of tip moth populations. When shoots are sampled and dissected, however, the number of nonviable tip moths can be determined and a more accurate association with trap

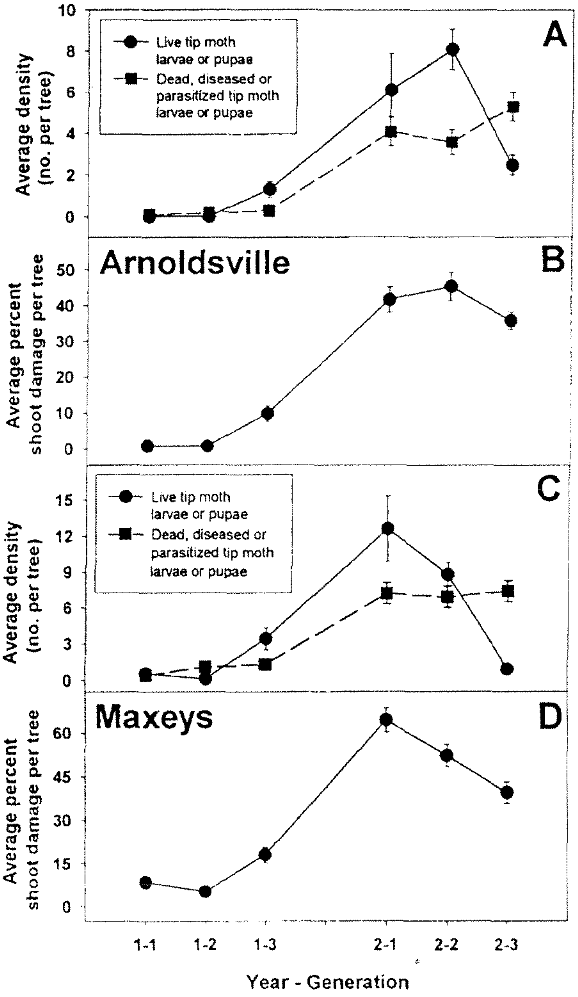

Fig. 7. Seasonal variation in tip moth density (A, C), mortality (A, C), and damage (B, D) over 2 yr at two sites in Oglethorpe County, GA. (A, B) Arnoldsville and (C, D) Maxeys.

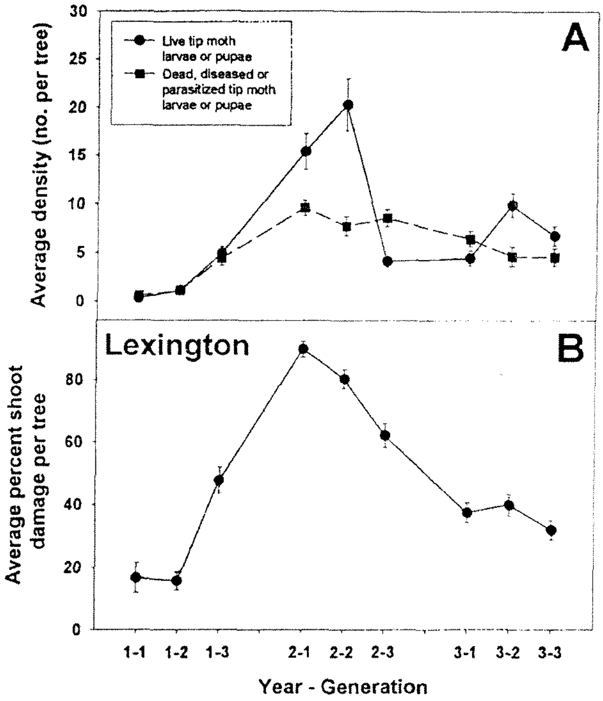

Fig. 8. Seasonal variation in tip moth density (A), mortality (A), and damage (B) over 3 yr at Lexington, Oglethorpe County, GA.

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. 5), 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. 6A, $y = 0.006$ [SE = 0.001]x - 2.175 [SE = 1.512]; $F = 39.83$; df = 1, 9; $r^2 = 0.83$; $P < 0.001$) and damage (Fig. 6B, $y = 0.024$ [SE = 0.003]x - 2.022 [SE = 5.114]; $F = 55.87$; df = 1, 9; $r^2 = 0.87$; $P < 0.001$) during the next generation using a linear model. However, total trap catch during the second adult generation was only a fair predictor of density (Fig. 6C, $y = 0.004$ [SE = 0.002]x + 1.299 [SE = 1.102]; $F = 2.59$; df = 1, 9; $r^2 = 0.24$; $P = 0.146$) and damage (Fig. 6D, $y = 0.047$ [SE = 0.021]x + 10.270 [SE = 9.463]; $F = 4.85$; df = 1, 9; $r^2 = 0.38$; $P = 0.059$) 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 (Table 1; Figs. 7 and 8), 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

Table 1. Average ±SE *R. frustrana* density, mortality, damage, and trap catch for each generation at each site in the Georgia Piedmont from 1997 to 2000

Site	Year	Generation	Avg no. moths per tree ($n = 40$)	Avg no. dead, diseased, or parasitized moths per tree ($n = 40$)	Avg % shoot damage per tree ($n = 40$)	Avg no. adult moths caught during entire trapping period ($n = 6$)	% of total moths caught prior to the spray date
Harve Mathis Road	1997	1	1.9 ± 0.6	0.9 ± 0.3	17.5 ± 3.1	1,101 ± 246	75.4
		2	3.4 ± 0.7	0.7 ± 0.2	20.4 ± 3.5	225 ± 51	80.9
		3	1.8 ± 0.6	2.1 ± 0.6	18.3 ± 3.2	129 ± 22	79.0
Bostwick	1997	1	0.9 ± 0.3	2.1 ± 0.4	13.6 ± 2.2	825 ± 115	82.4
		2	2.6 ± 0.6	1.4 ± 0.4	19.0 ± 2.8	227 ± 44	94.7
		3	1.4 ± 0.4	0.7 ± 0.2	8.9 ± 1.8	137 ± 22	77.4
Arnoldsville	1998	1	0.0 ± 0	0.1 ± 0.1	0.8 ± 0.8	36 ± 19	61.1
		2	0.0 ± 0	0.2 ± 0.1	0.7 ± 0.5	28 ± 14	78.6
		3	1.3 ± 0.4	0.3 ± 0.2	9.7 ± 2.3	113 ± 59	24.8
Maxeys	1998	1	0.5 ± 0.2	0.4 ± 0.2	8.3 ± 2.3	255 ± 68	73.7
		2	0.1 ± 0.1	1.1 ± 0.4	5.0 ± 1.5	144 ± 51	88.9
		3	3.4 ± 0.9	1.3 ± 0.3	18.0 ± 2.8	439 ± 93	23.0
Lexington	1998	1	0.3 ± 0.1	0.6 ± 0.2	16.7 ± 4.9	282 ± 96	73.4
		2	1.1 ± 0.3	1.1 ± 0.4	15.7 ± 2.9	326 ± 120	87.7
		3	4.9 ± 0.7	4.4 ± 0.7	47.7 ± 4.3	368 ± 81	30.7
Arnoldsville 2	1999	1	6.1 ± 1.8	4.1 ± 0.7	41.6 ± 3.6	1,947 ± 123	36.0
		2	8.1 ± 1.0	3.6 ± 0.6	45.3 ± 4.0	439 ± 81	72.0
		3	2.5 ± 0.5	5.3 ± 0.7	35.7 ± 2.6	344 ± 78	36.6
Maxeys 2	1999	1	12.6 ± 2.7	7.2 ± 0.9	64.3 ± 4.1	2,165 ± 342	47.0
		2	8.8 ± 1.0	6.9 ± 0.9	52.2 ± 3.8	487 ± 63	84.8
		3	0.9 ± 0.3	7.4 ± 0.9	39.4 ± 3.7	156 ± 40	33.3
Lexington 2	1999	1	15.4 ± 1.9	9.6 ± 0.8	89.8 ± 2.5	2,812 ± 356	60.1
		2	20.3 ± 2.7	7.7 ± 1.0	80.2 ± 3.1	714 ± 112	82.6
		3	4.1 ± 0.6	8.5 ± 0.9	62.1 ± 3.9	418 ± 117	34.0
Lexington 3	2000	1	4.4 ± 0.8	6.4 ± 0.8	37.4 ± 3.2	2,104 ± 274	77.6
		2	9.9 ± 1.2	4.6 ± 1.0	39.9 ± 3.4	744 ± 104	89.1
		3	6.7 ± 1.0	4.5 ± 0.9	31.9 ± 3.1	324 ± 52	72.8
Wilkes	2000	1	0.6 ± 0.2	1.6 ± 0.4	7.7 ± 1.8	1,360 ± 148	65.9
		2	2.2 ± 0.6	1.7 ± 0.4	14.8 ± 2.6	541 ± 77	91.5
		3	1.3 ± 0.3	1.7 ± 0.5	11.0 ± 2.1	178 ± 31	67.4

damage ($r = 0.33$) of the overwintering brood (Table 1).

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 et al. (2000b) reported control as low as 55.5% for the third generation when control for the first and second generations averaged 90.4 and 77.6%, 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 et al. 2000b).

Trap catch tallies used in the regression models (Fig. 6) were totals for the entire adult emergence period. This is not acceptable for practical use if trap catch is to be used to predict numbers or damage for subsequent generations because 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 before the spray date. Spray dates for many areas of the Southeast can be determined following the methods of Fettig et al. (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 before the spray date was 65.3% (±14.6) for the first adult generation, 85.1% (±6.7) for the second adult generation, and 47.9% (±23.1) for the third adult generation. During three of the four years of this study, these percentages were fairly consistent (Table 1). 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 et al. 2000a). Nevertheless, application of these percentages to the x-axis of Fig. 6 will provide predictive trap catch numbers before the spray date. For example, Fig. 6B demonstrates that catching 1836 moths (65.3% of 2,812) before the predicted optimum spray date during the first adult generation would result in 80% shoot damage per tree during the subsequent generation. Similarly, catching 539 moths (65.3% of 825) before the spray date during the first adult generation would result in ≈20% 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 <40% infested shoots may cause significant growth loss (Nowak and Berisford 2000, Fettig et al. 2000b; unpublished data). Therefore, Fig. 6B suggests that trap catches above 1,000 moths (≈65% of 1,500) before 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*% shoot damage on a tree that is one m tall will harbor a much smaller tip moth population than *x*% shoot damage on a tree that is three 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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