Efficacy of Wing Versus Delta Traps for Predicting Infestation Levels of Four Generations of the Nantucket Pine Tip Moth (Lepidoptera: Tortricidae) in the Southern United States

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ABSTRACT The use of pheromone trap catches to reliably predict damage by the Nantucket pine tip moth, *Rhyacionia frustrana* (Comstock), in loblolly pine (*Pinus taeda* L.) plantations would provide forest managers with a valuable integrated pest management tool. At 17 sites throughout four states in the southern United States, in areas where *R. frustrana* has four annual generations, adult moths were monitored throughout the year (2002) using two types of pheromone traps, and subsequent infestation levels were determined for each tip moth generation. Cumulative wing trap catch tallies up to published spray dates for three of four adult emergence periods were highly predictive of top whorl damage during the subsequent generation using linear regression models. Multiple linear regression that included initial average tree height as a covariate did not significantly improve model efficacy. Cumulative delta trap catch tallies up to the spray date were not predictive of subsequent damage levels for any tip moth generation using linear regression models. Although multiple linear regression incorporating tree height as a covariate did greatly improve delta trap model efficacy, the power and significance of these models remained insufficient. Wing traps seem to be much more sensitive to tip moth population change than delta traps; however, both are useful for monitoring seasonal activity and initiation of spray timing models.

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

THE NANTUCKET PINE TIP moth, *Rhyacionia frustrana* (Comstock), is an important and ubiquitous pest of loblolly pine (*Pinus taeda* L.) seedlings and saplings throughout the southern United States (Berisford 1988, Asaro et al. 2003). Its larvae initially mine needles and subsequently feed inside buds and shoots, where pupation and overwintering occur (Berisford 1988, Asaro et al. 2003). *R. frustrana* has two to five generations per year throughout its range, with three to four generations per year predominating (Fettig et al. 2000a). In heavy infestations, significant growth loss, stem deformity, and degrade can occur (Berisford and Kulman 1967, Hedden and Clason 1980, Yates et al. 1981, Fettig et al. 2000b). Loblolly pine plantation acreage along with intensive forest management practices (e.g., site preparation, herbicide, fertilizer) have increased significantly over the last 50 yr, and this trend is expected to continue (Nowak and Berisford 2000, Siry 2002). Numerous studies (Warren 1964, Berisford and Kulman 1967, Warren et al. 1974, Hertel and Benjamin 1977, Thomas et al. 1982, Nelson and Cade 1984, Hood et al. 1988, Ross et al. 1990, Nowak et al. 2003) have demonstrated a positive association between tip moth damage, intensive site preparation, and herbicide use. Therefore, control measures for *R. frustrana* are likely to be more widely used (Asaro et al. 2003), and forest managers will seek new management tools that increase the feasibility of widespread tip moth control.

Pheromone-baited sticky traps have been widely used in tip moth management, primarily for monitoring seasonal activity (Berisford 1974, Canalos and Berisford 1981) and for the application of spray-timing models (Berisford et al. 1984, Gargiullo et al. 1984, 1985, Fettig et al. 2000a). Asaro and Berisford (2001a) demonstrated that tip moth population density and damage were highly correlated with subsequent trap catch for each of three generations in the Georgia Piedmont using Pherocon 1C wing traps. Furthermore, cumulative trap catch of adult moths was highly to moderately predictive of subsequent damage levels from the first and second generation larval brood, respectively, using linear regression models (Asaro and Berisford 2001a).

However, some limitations of Asaro and Berisford (2001a) need to be addressed with additional research before pheromone-baited traps can be effectively

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Table 1. Location, coordinates, and initial tree heights (mean ± SEM) for all sites used in the 2002 study

Site name	State	County/parish	Town/city	Latitude	Longitude	Tree height (cm)
McBrayer	GA	Warren	Warrenton	33°34′	82°38′	45.3 ± 1.8
Clark-Johnson	GA	Warren	Warrenton	33°26′	82°38′	49.9 ± 2.6
Ashley Pannell	GA	McDuffie	Thomson	33°30′	82°35′	43.9 ± 1.5
Lloyd	GA	McDuffie	Thomson	33°26′	82°25′	38.0 ± 2.1
Evans-Nease	GA	Burke	Wrens	33°10′	82°10′	63.3 ± 3.9
IP-162	GA	Jefferson	Wrens	33°07′	82°16′	38.8 ± 1.9
IP-L29	GA	Burke	Waynesboro	33°04′	82°15′	42.1 ± 1.6
Alexander	GA	Jefferson	Louisville	32°59′	82°19′	38.8 ± 1.5
Rincon East	GA	Effingham	Rincon	32°17′	81°13′	84.9 ± 1.6
Rincon West	GA	Effingham	Rincon	32°17′	81°15′	94.9 ± 6.2
Hamilton No.	SC	Hampton	Estill	32°46′	81°15′	89.0 ± 2.4
Hamilton So.	SC	Hampton	Estill	32°44′	81°15′	91.8 ± 1.4
AB Porter	LA	Rapides	Alexandria	31°25′	92°54′	59.8 ± 2.1
Bejar	LA	Rapides	Alexandria	31°20′	92°48′	55.4 ± 1.6
Mudhole	LA	Rapides	Alexandria	31°16′	92°50′	54.4 ± 1.8
Stevens	TX	Nacogdoches	Woden	31°27′	94°50′	37.8 ± 2.2
Evans	TX	Cherokee	Rusk	31°45′	95°20′	33.4 ± 1.0

used for tip moth management. First, prediction models were limited to the first two generations, and the optimum spray date for controlling the next generation generally occurs before all of the adult moths from the current generation have emerged (Asaro and Berisford 2001a). Therefore, a predictive model based on trap catch can only use cumulative tallies of moths trapped up to the spray date. Also, damage estimates, which are typically expressed as the percentage of infested shoots (top whorl or whole tree), may not correlate adequately with trap catch data if tree height is not taken into consideration. For example, a 1-yr-old plantation with trees that are 0.5 m tall with 50% of the shoots infested will, on average, produce a much smaller population of moths than a 2-yr-old plantation with trees that are 2 m tall with comparable damage levels. This height difference is likely to be reflected in corresponding trap catches. Although Asaro and Berisford (2001a) attempted to control for this by selecting stands of trees that were the same age or of similar height, a useful damage prediction model must be robust to variable plantation age if it is to be useful and widely applicable. In addition, the prediction models of Asaro and Berisford (2001a) were based on 10 sites covering a limited area of the Georgia Piedmont. Validation of these models requires that we use more sites covering a significantly greater area. Furthermore, only three R. *frustrana* generations occur annually in the Georgia Piedmont, but loblolly pine production is much more extensive in the Coastal Plain region of the southern United States, where *R. frustrana* generally has four annual generations (Fettig et al. 2000a). Finally, although wing traps catch more moths than other trap types (Debarr et al. 2002), other less expensive traps used for tip moth monitoring, such as delta traps, have not been tested for damage prediction. A less expensive trap and reliable prediction from smaller trap counts would facilitate more widespread tip moth monitoring. Our objective was to validate previous models for predicting Nantucket pine tip moth damage levels by addressing the issues listed above.

Materials and Methods

Site Selection. Seventeen 1-yr-old plantations of loblolly pine were used, ranging from 20 to 96 ha each. Tree spacing ranged from 2 by 3 to 2 by 4 m, and weed competition was highly variable but not quantified. Ten sites were located in Georgia: eight in the upper Coastal Plain and two in the lower Coastal Plain. Two sites were located in the lower Coastal Plain of South Carolina, three in central Louisiana, and two in east central Texas (Table 1). All sites had four annual *R. frustrana* generations, and all data were collected during 2002. Data for one of the Louisiana sites (Mudhole) was not collected during the fourth generation because of access difficulties.

Pheromone Trap Catch. Traps were deployed either in December 2001 or early January 2002. At each site, four Pherocon 1C wing traps (white) and four Pherocon III delta traps (green; Trécé, Salinas, CA) were hung ≈1–1.5 m high in the tops of plantation trees or on steel conduit posts and placed systematically and alternately (i.e., wing-delta-wing-delta) throughout the center of the plantation at least 60 m apart and 30 m from the plantation edge. Pherocon 1C wing traps were only available in white, whereas Pherocon III delta traps were available in orange or green. A red rubber septa bait (Trécé) containing the *R. frustrana* two-component pheromone (Hill et al. 1981, Asaro et al. 2001) was placed in the center of each trap. Male tip moths were trapped from the start of each adult emergence period (January, May, June–July, and August) until the appropriate spray date for control of the subsequent generation was reached (Fettig et al. 2000a). Generation separation with trapping is possible because zero trap counts (or very low trap counts) generally occur between emergence periods; a subsequent increase in moths trapped indicates the start of the next emergence period. The cut-off date for trapping at each site and for each generation was the first day of the predicted spray windows, which were derived from degree-day accumulations and historical weather records for locations nearest each of the study sites (Fettig et al. 2000a).

Table 2. Data from July–August 2001 bait replacement test in which mean ± SEM weekly adult male trap catch was compared among traps containing no bait (control), baits replaced weekly, and baits that were not replaced throughout the test ($n = 4$ traps per treatment)

Month/week	Mean ± SEM		
	Control	Bait replacement	No bait replacement
July/1	0.00 ± 0a	2.25 ± 0.75a	3.00 ± 1.70a
July/2	0.00 ± 0a	11.25 ± 2.25b	18.25 ± 5.40ab
July/3	0.25 ± 0.25a	18.25 ± 5.80b	17.00 ± 3.50b
July/4	0.75 ± 0.50a	10.75 ± 2.70b	10.00 ± 1.60b
July–August/5	1.25 ± 0.60a	17.50 ± 4.00b	4.50 ± 0.90a
August/6	0.75 ± 0.75a	7.00 ± 1.80ab	8.25 ± 2.20b
August/7	0.25 ± 0.25a	19.00 ± 1.80b	8.25 ± 2.30c
August/8	0.50 ± 0.5a	12.75 ± 4.60b	1.50 ± 0.90a
August/9	0.00 ± 0a	17.25 ± 2.40b	0.50 ± 0.30a

Within each week, means followed by the same letter were not significantly different (Tukey's test, $\alpha = 0.05$).

Published spray dates for up to four generations of *R. frustrana* are available for most locations within Virginia, North and South Carolina, Georgia, Alabama, and Mississippi (Fettig et al. 2000a), as well as Texas, Louisiana, and Arkansas (Fettig et al. 2003).

Bait Replacement Test. In a field test conducted in a 2-yr-old loblolly pine plantation in Wilkes Co., GA, during July–August 2001, mean trap catch did not vary significantly for up to 6 wk among traps baited once with red rubber septa baits compared with traps with baits replaced weekly (Table 2). Thus, in this study, baits were replaced monthly during the first adult emergence period, which spanned 3–4 mo, from January to mid-March or early April. Bait replacement during subsequent trapping periods was not necessary because the time period spanning first adult emergence to the spray date does not generally exceed 4 wk.

Tree Height and Damage Estimates. In January or February, the height of six randomly selected trees within a 7.5 m radius of each pheromone trap was measured at each site. After each adult emergence period, top whorl damage estimates were obtained from 48 trees per site, selected in the same manner as described above. Shoots were counted within each top whorl, and the percentage of damaged shoots was determined. A shoot was defined as being at least 5 cm long and terminating in a bud. A damaged shoot becomes apparent when larval feeding causes a visible pitch mass to appear on or near the terminal bud as well as browning of needles near the terminus of the shoot. Voucher specimens have been deposited at the Entomology Collection at the University of Georgia, Athens, GA.

Statistical Analysis. All tests were performed using Sigmastat 2.0 (SPSS 1997). Trap catches among the bait replacement test treatments were compared using analysis of variance (ANOVA) followed by Tukey's test for means separation. Before regression analysis, scatter plots were examined to determine the most appropriate model, which was evaluated by looking at the r^2 value, degree of heteroscedasticity, and robustness (Sokal and Rohlf 1995). All regression models conformed to normality and equal variance assumptions, so regressions were performed on untransformed data. Relationships between average trap catch up to the spray date and average top whorl damage during the subsequent generation was described with simple linear regression models. In addition, multiple linear regression was performed by adding initial tree height to each of the previously generated models. Ten data points based on data from a previous study (Asaro and Berisford 2001a; Table 3) were added to the first and second generation prediction models for wing traps to improve model adequacy and robustness.

Results and Discussion

Simple linear models were all significant ($P < 0.001$) for wing traps predicting the first three of four tip moth generations while explaining 44–62% of the variation (Table 4; Fig. 1, A–C). Wing trap model prediction of the fourth generation was poor and insignifi-

Table 3. Location, coordinates, and initial tree heights (mean ± SEM) for all sites used in Asaro and Berisford (2001a)

Site name	State	County/parish	Town/city	Latitude	Longitude	Tree height (cm)
Harve Mathis	GA	Clarke	Athens	34°00′	83°19′	121.0 ± 4.2
Bostwick	GA	Morgan	Bostwick	33°44′	83°30′	142.0 ± 4.4
Arnoldsville	GA	Oglethorpe	Arnoldsville	33°54′	83°13′	43.5 ± 1.6
Maxeys	GA	Oglethorpe	Maxeys	33°46′	83°13′	49.3 ± 2.1
Lexington	GA	Oglethorpe	Lexingtion	33°48′	83°03′	40.7 ± 1.5
Arnoldsville 2	GA	Oglethorpe	Arnoldsville	33°54′	83°13′	113.7 ± 3.4
Maxeys 2	GA	Oglethorpe	Maxeys	33°46′	83°13′	108.7 ± 3.7
Lexington 2	GA	Oglethorpe	Lexingtion	33°48′	83°03′	91.8 ± 2.9
Lexington 3	GA	Oglethorpe	Lexington	33°48′	83°03′	163.2 ± 4.9
Wilkes	GA	Oglethorpe	Rayle	33°47′	83°01′	154.7 ± 6.0

cant (Table 4; Fig. 1D). For each generation, multiple linear regression using tree height as a covariate did not greatly improve the power of the model or explain much additional variation (Table 4). The scale of trap catch up to the spray date decreased systematically from the first generation prediction model (≈0–1,800 moths) to the second (≈0–650 moths) and from the second to the third and fourth generation prediction models (≈0–250 moths, respectively; Fig. 1, A–D). For each generation, damage levels predominately ranged from 0 to 60% (Fig. 1, A–D).

Simple linear models were all insignificant ($P > 0.05$) for delta traps predicting each of four generations while they explained 2–18% of the variation (Table 4; Fig. 2, A–D). Multiple linear regression using tree height as a covariate dramatically improved the power of the model in each case and explained significantly more variation than trap catch alone (Table 4). However, these models still had undesirably low power, and in all but one case, multiple linear regression models were statistically insignificant. The scale of trap catch up to the spray date decreased from the first generation prediction model (≈100–550 moths) to the second (≈0–160 moths) and decreased from the second to the third and fourth generation prediction models (≈0–60 and 0–100 moths, respectively; Fig. 2, A–D). For each generation, damage levels predominately ranged from 0 to 60% (Fig. 2, A–D).

Data from Asaro and Berisford (2001a) were used to augment the data set for the first and second generation wing trap prediction models (Fig. 1, A and B). This was justified for the following reasons. (1) In all four delta trap models (Fig. 2, A–D), data throughout the range of trap catch values was highly scattered, and it is improbable that additional data would have greatly improved their usefulness. In contrast, with the exception of a few notable outliers, most of the data points from the first and second generation wing trap models conformed quite closely to the model throughout the range of x values. (2) The third generation wing trap prediction model was the most predictive (Fig. 1C) of the four despite having as many data points (17) as the delta trap models. (3) Although the fourth generation wing trap model was the least predictive of the four (Fig. 1D), it was still as predictive as the best of the delta trap models with only 16 data points (Fig. 2A). Our data show that delta traps are poor predictors of tip moth damage compared with wing traps. Debarr et al. (2002) found no significant differences in *R. frustrana* pheromone trap catch among white, green, or orange traps; therefore, trap color probably did not influence these results. Because delta traps are less costly and fewer moths have to be counted, they would have been preferred if they were as effective as wing traps.

Because airflow through delta traps is unidirectional, their efficacy is more dependent on wind direction. When male tip moths follow the pheromone plume of a pheromone-baited delta trap, they can become disoriented on approach if the wind direction is perpendicular to the trap opening (C. W. B., personal observation). Wing traps are open on all sides

Table 4. Statistical parameters for all regression equations presented in the study

Trap type	Predicted generation/ model type	Regression model coefficients[a] (±SEM)	F	df	P	R^2	Resid. MSE	Power
Wing	First/simple linear	$y = 10.026(4.426) + 0.030(0.005)x$	28.19	1, 26	<0.001	0.53	175.8	0.995
	First/multiple linear	$y = 12.953(5.746) + 0.032(0.006)x_1 - 0.063(0.078)x_2$	14.22	2, 26	<0.001	0.54	178.3	0.996
	Second/simple linear	$y = 12.784(4.492) + 0.062(0.014)x$	19.60	1, 26	<0.001	0.44	183.3	0.974
	Second/multiple linear	$y = 16.828(6.197) + 0.066(0.015)x_1 - 0.067(0.071)x_2$	10.21	2, 26	<0.001	0.46	184.1	0.981
	Third/simple linear	$y = 11.747(4.373) + 0.217(0.044)x$	24.92	1, 16	<0.001	0.62	100.3	0.980
	Third/multiple linear	$y = 20.314(8.989) + 0.205(0.045)x_1 - 0.133(0.123)x_2$	13.20	2, 16	<0.001	0.65	99.1	0.987
	Fourth/simple linear	$y = 31.867(8.405) + 0.108(0.062)x$	3.04	1, 16	0.103	0.18	307.3	0.369
	Fourth/multiple linear	$y = 37.736(19.187) + 0.098(0.071)x_1 - 0.082(0.239)x_2$	1.48	2, 16	0.263	0.19	328.0	0.383
Delta	First/simple linear	$y = 35.390(7.165) - 0.041(0.022)x$	3.32	1, 26	0.088	0.18	123.6	0.398
	First/multiple linear	$y = 42.809(7.569) - 0.005(0.027)x_1 - 0.163(0.321)x_2$	3.92	2, 26	0.045	0.36	103.7	0.735
	Second/simple linear	$y = 15.554(8.035) + 0.096(0.086)x$	1.25	1, 26	0.280	0.08	238.0	0.186
	Second/multiple linear	$y = 34.781(12.476) + 0.086(0.080)x_1 - 0.325(0.170)x_2$	2.57	2, 26	0.112	0.27	202.1	0.575
	Third/simple linear	$y = 21.627(6.928) + 0.321(0.227)x$	2.00	1, 16	0.178	0.12	235.6	0.267
	Third/multiple linear	$y = 39.495(10.197) + 0.449(0.210)x_1 - 0.374(0.170)x_2$	3.69	2, 16	0.052	0.34	187.4	0.712
	Fourth/simple linear	$y = 39.280(10.022) + 0.098(0.169)x$	0.33	1, 16	0.573	0.02	365.3	0.08
	Fourth/multiple linear	$y = 51.936(15.614) + 0.117(0.169)x_1 - 0.241(0.228)x_2$	0.72	2, 16	0.503	0.10	362.4	0.218

[a] For simple linear models, x = slope (trap catch); for multiple linear models, x_1 = trap catch, x_2 = tree height.

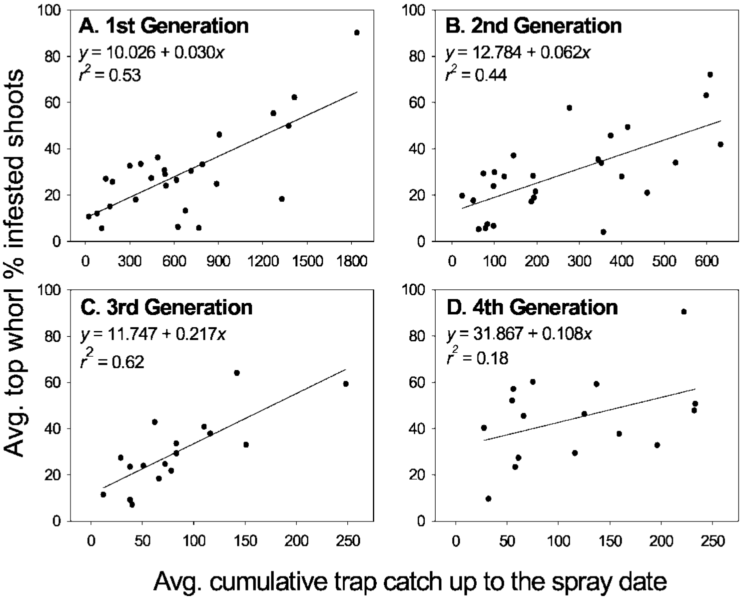

Fig. 1. Linear regression models predicting average top whorl damage to loblolly pines for each of four tip moth generations (A-D) based on average cumulative wing trap tallies up to the spray date for each generation.

and are less affected by wind direction. In addition, wing traps have a larger sticky surface. As a result, wing traps are generally capable of catching greater numbers of moths, have lower variation in catch, and seem to be more sensitive indicators of tip moth population levels. However, delta traps are as effective as wing traps for monitoring tip moth phenology and initiating spray-timing models.

The quantity of tip moths caught per trap per day was always significantly greater during the spring emergence than subsequent emergence periods in this and an earlier study (Asaro and Berisford 2001a), even when population densities across generations were equal. Asaro and Berisford (2001b) demonstrated that adult male tip moth life span is significantly shorter during hot weather and showed how this might influence daily trap catch, although other explanations were considered. The quantity and ratio of pheromone components was shown to be stable between *R. frustrana* generations (Asaro et al. 2001). The num-

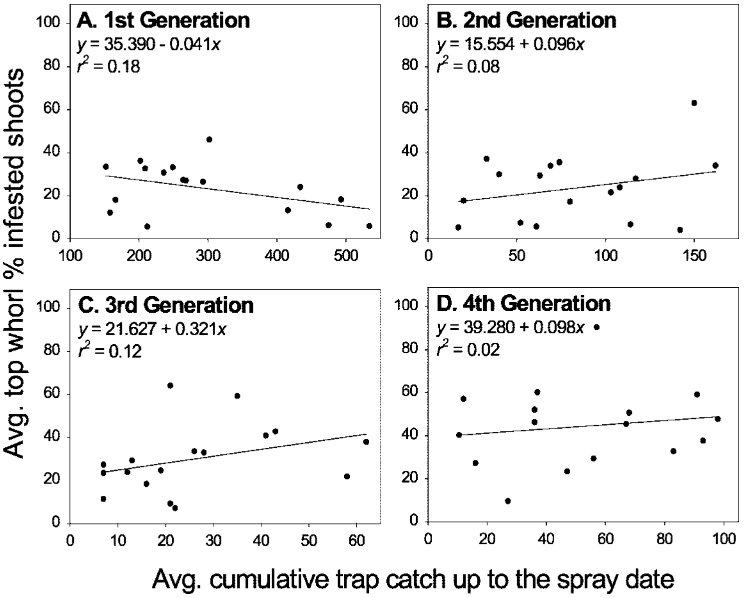

Fig. 2. Linear regression models predicting average top whorl damage to loblolly pines for each of four tip moth generations (A-D) based on average cumulative delta trap tallies up to the spray date for each generation.

ber of moths caught up to the spray date decreased still further during the third and fourth emergence period compared with the second period. Although temperatures during the third and fourth emergence periods (July–September) are likely to be slightly warmer than those during the second period (May–June), catch reductions might also occur because tip moth development is less synchronous and adult emergence more gradual. Consequently, spray dates typically fall much earlier along the emergence peak compared with earlier tip moth generations. However, none of this appears to impact the usefulness of the regression models, only the scale of the independent variable.

The lack of any significant improvement in wing trap model adequacy from using multiple linear regression was unexpected. Variation in initial tree height between sites (Tables 1 and 3) was predicted to influence trap catch, as discussed previously. However, wing trap catch was adequate at predicting subsequent damage for the range of tree heights seen in this study (33.3–162.2 cm). The delta trap simple linear models were improved by adding initial tree height to the model because they initially had such low predictive power and significance. Percent damage as it relates to trap catch may only be sensitive to tree height within generations (i.e., predicting trap catch based on previous damage), but not between generations (i.e., predicting subsequent damage based on current trap catch) as we hypothesized. Although stands with smaller trees produce fewer moths than stands of larger trees with comparable infestation levels, fewer moths are required to cause the same infestation levels during the next generation in stands with smaller trees. Thus, the proportionality of percent damage is carried over from one generation to the next and tree height becomes irrelevant, within certain bounds. The simple linear regression models presented here seem to be robust for plantations that are 1–5 yr old. However, we do not recommend using these models in plantations older than 5 yr or those in which trees are taller than 2.5 m at the start of the growing season; generally, tip moth control is not necessary when trees reach this level of maturity (Berisford 1988, Asaro et al. 2003).

This study was replicated over a wide area of the southern United States to make up for the lack of temporal replication. There is little reason to expect changes in the fundamental relationship between trap catch and subsequent tip moth damage over multiple seasons. Therefore, site replication should be more important, provided there is a wide enough range of damage levels to produce a useful regression. Although we only collected data for one season, the slopes of the regression lines for the first and second generation wing trap models ($0.030x$ and $0.062x$, respectively) in this study were similar to those presented in Asaro and Berisford (2001a) ($0.024x$ and $0.047x$, respectively; data collected over four seasons). Therefore, the general linear relationships between trap catch and subsequent damage for these two generations as presented in Asaro and Berisford (2001a) were highly robust to additional data. However, there is always a need for more data, particularly that which relates trap catch to heavier damage levels (i.e., >60%) to develop more reliable models.

Although there is considerable variation in emergence times and number of generations across the range of *R. frustrana,* this does not greatly impact the models presented herein. Typically 60–80% of the moths emerge by the spray date regardless of the date of initial emergence or the length of time for the entire emergence period. Although five generations occur in the extreme southern portion of the moth's range (Fettig et al. 2000a, 2003), we chose not to model this generation for the following reasons: (1) slash pine (*Pinus elliottii* Engelmann) and longleaf pine (*Pinus palustris* Miller), which are resistant to Nantucket pine tip moth (Asaro et al. 2003), are the predominant plantation species in most areas with five generations; (2) the fifth generation is often difficult to distinguish from the fourth, and it is highly unlikely that chemical control of a fifth generation would ever be economical; and (3) because the fourth generation wing trap prediction model was quite poor relative to the first three, it seems unlikely that a fifth generation prediction model would be much better.

The presence of outliers in the first generation wing trap model (Fig. 1A) significantly reduced its r^2 value. Although these points were not removed, an explanation for such outliers is warranted. Asaro and Berisford (2001a) demonstrated that predicting damage based on trap catch would fail on occasion when drastic changes in parasitism rates occur between generations. For example, there are four outliers in Fig. 1A that lie well below the regression line. This can occur if trap catch overestimates subsequent damage because parasitoids of eggs and young larvae suppress the subsequent population (Asaro and Berisford 2001a). Unfortunately, parasitism of the next generation cannot be predicted because it occurs after the spray date. Therefore, there is always a risk that trap catch of the current generation will not adequately reflect future damage levels (it happens ≈15% of the time when predicting the first generation, based on the current data set). Occasionally overestimating the population means one might use chemical control when it is not necessary.

We provide an example of how these models can be used in practice (Fig. 3). Using the first generation wing trap prediction model (Fig. 1A), it becomes clear how to use the regression line and hypothetical delineations of low, moderate, and heavy damage to reach a management decision regarding the next generation. With low damage, chemical control would not be warranted; with heavy damage, it is likely to be economical. The moderate damage category is more ambiguous, and whether spraying is economical would probably depend on other factors such as site quality and tree genetics. It is important to note, however, that there are no documented economic thresholds for *R. frustrana;* the damage categories (Fig. 3) are subjective and are based on our own judgment and experience.

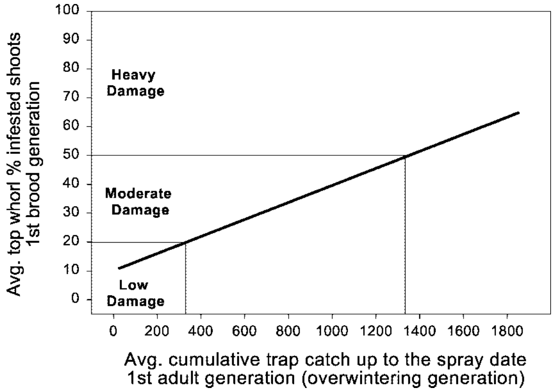

Fig. 3. Diagrammatic illustration of how to use the wing trap regression model A to forecast subsequent damage levels (first generation brood) and make a decision regarding insecticide application. The cut-off values delineating low, moderate, and heavy damage are hypothetical.

Although these models are based on cumulative catches up to the spray date, forest managers will want to have a greater window of time with which to plan spray operations. For example, cumulative trap catch up to 1 or 2 wk before the spray date might allow for sufficient lead-time for which to plan a spray operation. Using the raw wing trap catch data from this study, we calculated the percentage of total moths likely to be caught up to 4 wk before the spray date at weekly intervals for the first three adult emergence periods (Table 5). For example, during the first adult emergence period, ≈82% of the moths caught by the spray date will be trapped 1 wk before the spray date. Therefore, if our cumulative trap catch averages 1,200 moths at 1 wk before the spray date during the spring emergence, we would catch ≈1,463 (1,200/0.82) moths by the spray date. Using our model for the first adult emergence (Fig. 3), this number of moths suggests we should anticipate heavy damage during the subsequent generation. Note, however, that as we pull back further from the spray date, the percentage of moths caught becomes less reliable an indicator of subsequent damage based on the increase in variance and the coefficient of variation. In addition, pulling back from the spray date during the second and third adult emergence period is less reliable because a larger proportion of the total population is caught during a shorter time span in the summer than in the spring; thus, backing off a week from the spray date during summer will miss a greater proportion of the population than a week in the early spring.

Table 5. Mean ± SEM percentage of trapped moths up to the spray date (SD) for each of three adult emergence periods at each of four weekly intervals before the spray date (n = 27)

Generation (adult)	Percentage of total moths caught by the spray date at four weekly time intervals (mean ± SEM)			
	SD − 1 wk	SD − 2 wk	SD − 3 wk	SD − 4 wk
1	82.3 ± 2.1	67.4 ± 2.8	52.8 ± 4.1	40.6 ± 4.3
2	81.8 ± 2.8	53.0 ± 4.0	24.5 ± 3.9	3.5 ± 1.0
3	68.1 ± 5.8	53.4 ± 6.0	16.4 ± 3.2	8.7 ± 2.2

These data add to the use of pheromone traps as tools for Nantucket pine tip moth management. The models presented herein are simple and can predict low versus heavy damage with a high degree of confidence, although pheromone traps might not be sensitive enough to greatly facilitate chemical control decisions at intermediate trap catch levels. Asaro et al. (2003) presented a management protocol for the Nantucket pine tip moth that incorporates the tools that are currently available, including cumulative trap catch as a predictor of subsequent damage (based on Asaro and Berisford 2001a). These recommendations need only be modified slightly based on data from the current study. Forest managers may be encouraged to use these relatively simple tools as part of an overall integrated pest management strategy for loblolly pine plantations.

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