Variation in Developmental Synchrony of the Nantucket Pine Tip Moth (Lepidoptera: Tortricidae) with Implications for Chemical Control[1]

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Abstract Regional variation in developmental phenology of the Nantucket pine tip moth, *Rhyacionia frustrana* (Comstock), was studied at four locations in southeastern Virginia and northeastern North Carolina. A companion study assessed the effects of developmental asynchronony on insecticide spray timing efficacy. Substantial variation in developmental synchrony was found within a relatively small area, with more synchronous development at Greensville and Isle of Wight Co., VA sites, and high levels of asynchrony at Sussex Co., VA, and Hertford Co., NC, sites. The Greensville Co. site showed a typical three generation developmental phenology, while the Isle of Wight Co. site had a more atypical two generation phenology. The Sussex and Hertford Co. sites appeared to have phenologies that were a combination of the other two sites. Spray timing evaluations with permethrin at the Sussex Co. site suggested that mid-April to early May and early to mid-July periods offer opportunities for effective chemical control of tip moths. These dates corresponded to the presence of high proportions of eggs and early-instar larvae in the field. Later season sprays were largely ineffective due to high developmental asynchrony, which resulted in the presence of high proportions of late-stage tip moths on virtually all collection and spray dates. Results suggest that multiple late-season treatments likely would be more effective. Overall, optimal spray dates at the Greensville Co. site, which had a typical three-generation tip moth developmental pattern, agreed most closely with published optimal spray period predictions which are based on historical temperature data.

Key Words *Rhyacionia frustrana, Pinus taeda,* spray timing, developmental synchrony

The Nantucket pine tip moth, *Rhyacionia frustrana* (Comstock), is an important pest of young pine plantations in the southern United States, attacking seedlings and saplings of loblolly (*Pinus taeda* L.), shortleaf (*P. echinata* Miller), and Virginia (*P. virginiana* Miller) pines (Berisford 1988, Asaro et al. 2003). The economic importance of this insect appears to have grown in association with increasingly intensive commercial forest management practices (Hertel and Benjamin 1975, Ross et al. 1990, Nowak and Berisford 2000). Eggs are deposited on needles and shoots. Early-instar larvae mine the needles. Later instars feed on the meristematic tissue of shoots and buds, which can cause reduced height and volume growth (Stephen et al. 1982, Cade and Hedden 1987, Nowak and Berisford 2000), poor tree form (Berisford and Kulman

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1967, Lashomb et al. 1978, Berisford et al. 1989), and decreased wood quality due to formation of compression wood (Hedden and Clason 1980). There are five larval instars. The moths are multivoltine, with two to five generations annually, depending on climate (Ross et al. 1989, Fettig et al. 2000a). Three generations occur in the southeastern Virginia and northeastern North Carolina coastal plain (Fettig and Berisford 1999, Fettig et al. 2000a). The moths overwinter as pupae inside dead shoots and buds.

Chemical control can effectively reduce tip moth damage and associated volume losses (Young et al. 1979, Nowak and Berisford 2000). Permethrin (Pounce® 3.2 EC, FMC, Philadelphia) is a commonly used insecticide for tip moth control. It has low mammalian toxicity and is effective in reducing tip moth damage (Fettig et al. 2000b). Optimal spray timing, using degree-day models, can increase insecticide efficacy and reduce application frequency (Gargiullo et al. 1983, Berisford et al. 1984, Gargiullo et al. 1984, 1985, Fettig et al. 1998, Nowak et al. 2000). This procedure involves summing accumulated degree-days until an experimentally determined sum is reached. This sum indicates the optimal spray date for each generation and is based on moth phenology and insecticide properties. Eggs and early-instar larvae are targeted; later stages are relatively unaffected by sprays once they have entered the shoot (Fettig and Berisford 1999). Recently, Fettig et al. (2000a, 2003) and Fettig and Berisford (2002) developed a simplified spray timing system using long-term historical temperature data. This system predicts optimal spray intervals based on 5-day periods for 504 locations across the southeastern United States from VA to TX. It provided generally adequate control in numerous validations and has the potential for meeting spray timing objectives while being less labor intensive than degree-day models.

Spray timing models have been developed for controlling tip moth infestations in several geographic locations, including eastern Virginia and North Carolina (Fettig and Berisford 1999). However, chemical control has generally been ineffective in certain areas of the southeastern Virginia and northeastern North Carolina coastal plain, apparently due to an unusually high degree of developmental asynchrony that occurs in some populations (Fettig and Berisford 1999). We undertook a study to (1) examine the developmental phenology of the Nantucket pine tip moth in the Virginia and North Carolina coastal plain, and (2) evaluate the potential for control of Nantucket pine tip moth in that region using spray timing.

Materials and Methods

Developmental phenology. Tip moth developmental phenology was studied from March through October 1998 at four loblolly pine plantations in the southeastern Virginia and northeastern North Carolina coastal plain. One plantation was located in Hertford Co., NC, near Murfreesboro (36.44°N, 77.10°W). The remaining three were located in Isle of Wight, Sussex, and Greensville counties, VA, near Windsor (36.81°N, 76.74°W), Wakefield (36.97°N, 76.99°W), and Emporia (36.69°N, 77.53°W), respectively. All were 2-yr-old plantations except for the Isle of Wight plantation, which was 3 yrs old. All sites had received intensive site preparation and herbicide applications for control of competing vegetation, and had large windrows containing woody debris. Degree-days were accumulated at each site with a continuously recording biophenometer (Model T151®, Dataloggers Inc., Logan, UT). Biophenometers were set to a lower threshold of 9.5°C and an upper threshold of 33.5°C. The lower value represents an average of the male moth flight and egg development threshold, and the higher value the upper limit for successful egg development to occur (Haugen and Stephen 1984, Garguillo et al. 1985). Immature tip moth life stages were monitored by collection of shoots from 10 to 15 trees at each site. Each tree was selected by walking a randomly determined distance and direction within the stand. Three shoots were collected from each tree: one from the top whorl of shoots, one from the vertical midpoint of the crown, and one midway between the vertical midpoint and top whorl. Shoots nearest a randomly determined direction were collected. The entire shoot plus 5 cm of the woody branch was taken. Degree-day recordings and shoot collections were done every 3 or 4 days at each site throughout the study period. Shoots were taken to the laboratory, dissected, and numbers of moth eggs, larvae, and pupae per shoot were determined and recorded. Head capsule widths were measured to determine larval instars (Fox et al. 1971). At the end of the study period, temporal patterns of tip moth development were compared among sites and with degree-day accumulations. Simpson's dominance index, a component of Simpson's diversity index (Simpson 1949), was calculated for life stages present at each site for one collection per week. The dominance index is a measure of the concentration of individuals among different groups, and ranges from zero for lowest dominance (*N* individuals evenly distributed among *N* different groups) to 1.0 for highest dominance (all individuals in one group). The dominance index was used to quantify the developmental synchrony at each site, with high synchrony being reflected by tip moths concentrated in fewer life stages, and high asynchrony reflected by tip moths more evenly distributed among many life stages. Dominance indices were calculated for dates from mid-April to mid-September to exclude the highly synchronized development found at the beginning and end of the season soon after spring emergence and at the onset of pupal overwintering. Dominance indices were compared among sites using the Kruskal-Wallis one-way analysis of variance on ranks. Pairwise comparisons were performed using Dunn's method.

Spray timing. The spray timing study was conducted at the Sussex Co. site, an area where operational control attempts had been unsuccessful. The study was begun in mid-April, 1998, and continued through mid-October. Three randomized complete blocks were established, with 54 plots in each block and 6 trees in each plot. Every 3 or 4 days, one randomly selected plot in each block was treated with permethrin (Pounce® 3.2 EC), mixed at 1.0 ml concentrate to 2.07 L water. Early spring treatments were applied weekly due to slow tip moth development. One check plot in each block was left untreated each generation. Insecticide was applied with a 7.57 L pump pressure sprayer (Solo®, Virginia Beach, VA) until trees were uniformly covered. One plot received two sprays (28 April and 15 May) in the first generation, and another plot received two sprays (9 August and 30 August) in the third generation, to evaluate the effectiveness of multiple treatments. To evaluate the potential effect of tip moth control on tree growth, heights of all treatment and check trees were measured at the end of the first and second generations.

Efficacy of spray treatments on different dates was evaluated for each tip moth generation using percentage of shoots showing tip moth damage, obtained from whole tree counts. Damage assessments were made on 10 June, 5 August, and 23 October for first (spring), second (summer), and third (late summer) generations, respectively, when shoot damage was evident. Differences in mean percentage infestation rates among plots were analyzed using two-way ANOVA on the arcsine-transformed percentages. The Bonferroni *t*-test was used to compare each treatment mean to the check. Mean heights of trees in plots showing the most effective tip moth control (first generation—five plots with mean percentage damage less than 20%; second generation—four plots with mean percentage damage less than 15%) were compared with mean heights of trees in remaining plots using students *t*-test. These percentages were chosen because they represented the clearest threshold of insecticide efficacy. All statistical analyses were done using Sigma Stat, version 4.01 (Jandel Scientific 1994).

Results and Discussion

Life stage sampling showed substantial variation in developmental synchrony of tip moth populations. Tip moth developmental phenology was highly asynchronous at the Hertford Co. and Sussex Co. sites, where, after mid-May, substantial numbers of third to fifth instars were present at virtually all times. Peak densities of eggs and first instar larvae were poorly defined (Figs. 1, 2). In contrast, tip moth phenology at the Greensville Co. and Isle of Wight Co. sites showed more discrete life stage developmental peaks (Figs. 3, 4). Median dominance indices were significantly higher at the Greensville Co. and Isle of Wight Co. sites than at the other two sites (Fig. 5), demonstrating that the level of tip moth developmental synchrony can vary substantially even at locations within approximately 50 km of each other. This possibility should be considered when spray timing models produce poorer than expected tip moth control. It is also possible that the level of tip moth developmental synchrony could affect tip moth parasitism rates. Numerous studies have documented the im-

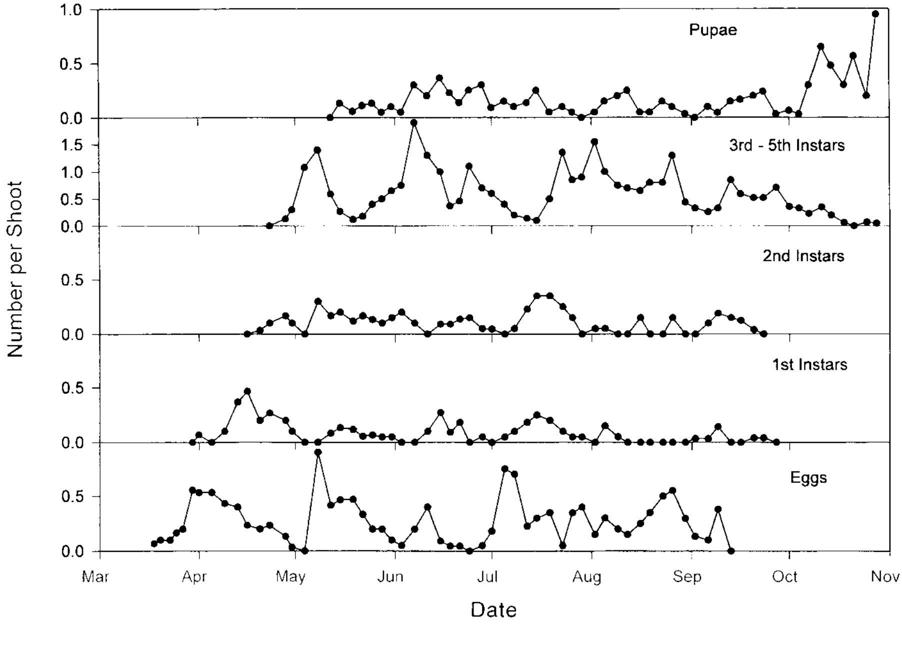

Fig. 1. Numbers of Nantucket pine tip moths present per loblolly pine shoot in Hertford County, NC, 1998. Tick marks along x-axis indicate beginning of month.

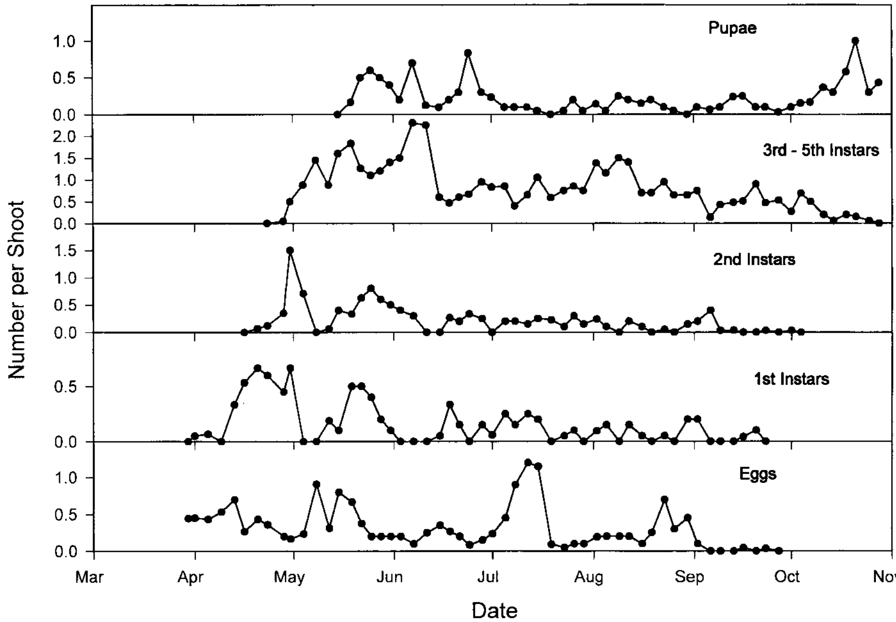

Fig. 2. Numbers of Nantucket pine tip moths present per loblolly pine shoot in Sussex County, VA, 1998. Tick marks along x-axis indicate beginning of month.

portance of parasitoids as agents of tip moth mortality (Asaro et al. 2003). If parasitoids attack specific tip moth life stages, then highly asynchronous tip moth development could adversely affect the ability of searching parasitoids to locate appropriate hosts. On the other hand, this developmental asynchrony may act to ensure that some suitable tip moth life stages are present at virtually all times.

The extreme western Greensville Co. site showed a fairly typical tip moth phenology that would be expected for the region, with three well defined generations and perhaps a partial fourth arising from a small emergence from pupae present in early September (Fig. 3). However, the extreme eastern Isle of Wight Co. data suggest only two generations, with a partial third, which may also arise from an emergence of pupae present in early September (Fig. 4). Hertford Co. and Sussex Co. are intermediate in location between the other two counties. When viewed in this light, tip moth phenologies of the Hertford Co. and Sussex Co. sites (Figs. 1, 2) could be a combination of those of the other two sites, with anomalous phenologies intermixed. Additionally, all four sites had large numbers of late-instar larvae present in late July and August (Figs. 1-4), suggesting the possibility that these larvae estivate for some period before entering the overwintering pupal stage. Further investigation is needed to determine the geographic range and the causes of these anomalous phenologies.

First generation insecticidal treatments produced the most effective tip moth control, with mid-April to early May treatments reducing infestations to 2 to 17%, vs a mean percent infestation of 61.41 ± 3.22 for the check trees (Fig. 6). These dates corresponded to peak ratio of eggs and first instar larvae to late-instar larvae present

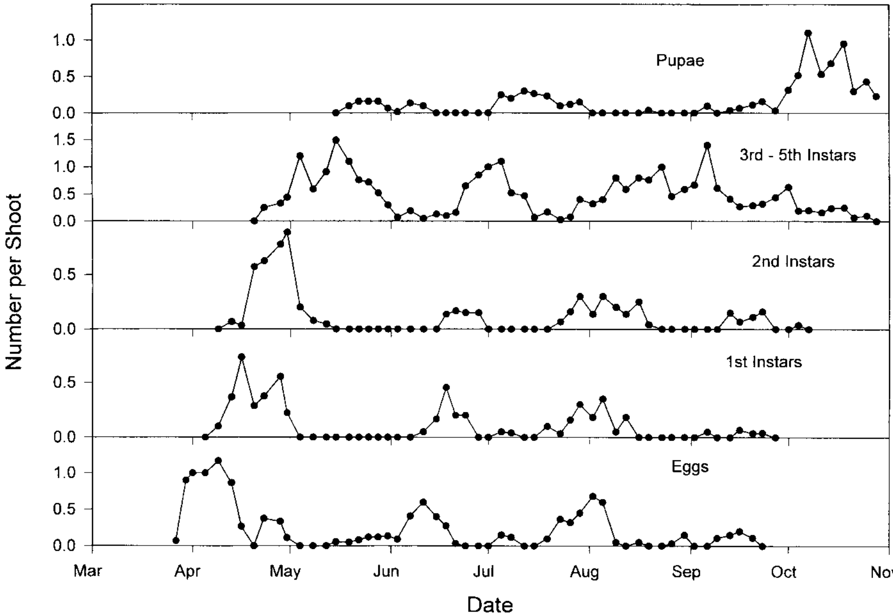

Fig. 3. Numbers of Nantucket pine tip moths present per loblolly pine shoot in Greensville County, VA, 1998. Tick marks along x-axis indicate beginning of month.

in the field (Fig. 2), suggesting that permethrin killed eggs and/or newly-hatched larvae. The increased efficacy of early generation insecticidal treatments is generally attributed to high life stage synchrony, but may also be due to high proportions of early-instar larvae exposed on the shoots during the initial generation (Fettig and Berisford 1999). Relatively large numbers of exposed first generation early-instar larvae were noted in the present study. The two-spray treatment (28 April and 15 May) produced the greatest efficacy (Fig. 6), probably by causing high mortality among two relatively distinct cohorts of eggs/early instars. This suggests that multiple first generation sprays may be advantageous, because control of the first generation appears to be most important in tip moth management (Fettig et al. 2000b). Efficacy decreased dramatically beginning with the 12 May treatment, though early to mid-May treatments still produced significantly reduced infestations compared to untreated checks. This coincided with increased abundance of mid- and late-instar tip moth larvae (Fig. 2). The optimal spray date of 28 April (Fig. 6, Table 1) was within the optimal spray period modeled (using long-term average temperatures) by Fettig et al. (2000a) for this location. This optimal spray date, as well as those for the following two generations, corresponded to the presence of high densities of eggs/early-instar larvae (Fig. 2).

The most effective treatments during the second generation reduced infestation rates to approximately 10%, and were from early to mid-July (Fig. 6), with decreased efficacy occurring as the ratio of eggs and first-instar larvae to late-instar larvae

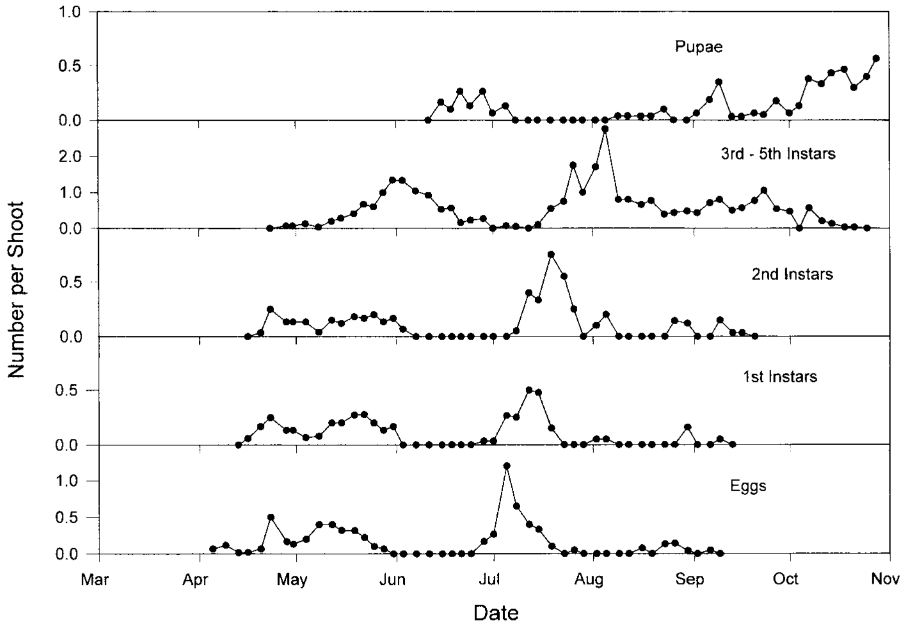

Fig. 4. Numbers of Nantucket pine tip moths present per loblolly pine shoot in Isle of Wight County, VA, 1998. Tick marks along x-axis indicate beginning of month.

decreased (Fig. 2). Mean percent infestation of check trees was 54.46 ± 4.16. The optimal spray date was 12 July (Fig. 6, Table 1). These dates were substantially later than the 20 to 24 June optimal spray period predicted from historical temperature data by Fettig et al. (2000a). However, significant reduction in tip moth infestation rates occurred as early as 28 June in our study. It should be noted that, because of the multiple peaks of susceptible life stages occurring at this site, assessment of spray timing efficacy is difficult, particularly late in the season. To an extent, the estimated optimal spray periods depend on the timing of damage assessment, since the multiple broods cause damage at different times.

Third generation treatments were generally ineffective, with no single treatment date reducing infestation rates below 20%. This was probably due to the very high late-season developmental asynchrony at this site (Fig. 2). Mean percent infestation of check trees was 55.61 ± 5.10 (Fig. 6). Two spray applications (9 August and 30 August) reduced mean infestation levels to 14%, presumably by causing high mortality among two cohorts of early-instar larvae (Fig. 6). However, it is questionable if significant economic gains would be achieved through multiple sprays in the third generation. The most effective single spray date was 19 August (Fig. 6, Table 1), again later than the optimal spray period of 30 July to 3 August calculated by Fettig et al. (2000a). However, statistically significant reductions in tip moth infestation rates occurred throughout August, reflecting highly asynchronous late season tip moth development (Figs. 2, 6).

Site-specific optimal spray dates and degree-day accumulations for the Hertford

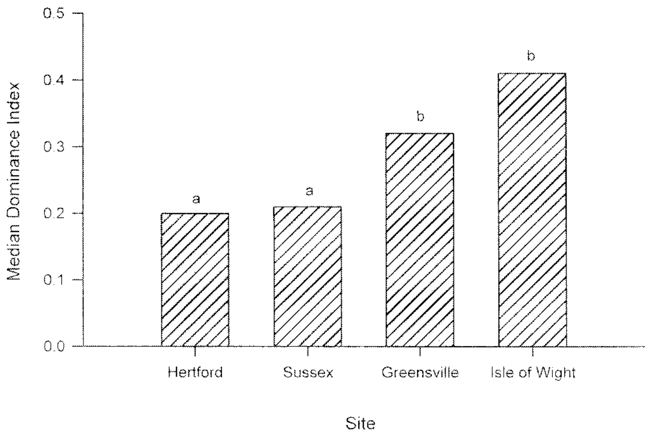

Fig. 5. Median Simpson's dominance indices for Nantucket pine tip moth life stages at four sites in southeastern Virginia and northeastern North Carolina. Bars with different letters are significantly different ($P < 0.05$, Kruskal-Wallis test, Dunn's multiple comparison method).

Co., Greensville Co. and Isle of Wight Co. sites, based on peak occurrence of eggs and first-instar larvae, are also shown in Table 1. Optimal spray dates for all Hertford Co. tip moth generations were 2 to 3 wks later than optimal spray periods calculated by Fettig et al. (2000a). The Greensville Co. first generation optimal spray date of 9 April in our study (Table 1) was 2.5 wks earlier than the optimal spray period given by Fettig et al. (2000a) for this location. Our 18 June second generation optimal spray date was within 2 days of that suggested by Fettig et al. (2000a), as was our 5 August third generation date. Our first generation optimal date of 12 May for Isle of Wight was roughly 2 wks later than the optimal spray period given by Fettig et al. (2000a) for nearby Suffolk. Optimal spray dates for the second and third generations for this location were also 2 to 3+ wks later than those given by Fettig et al. (2000a), due to the anomalous tip moth developmental phenology at this site.

Mean height of trees with less than 20% first generation tip moth infestation (13 April, 20 April, 28 April, 2-spray, and 4 May) was significantly greater than heights of trees with higher infestation levels (mean = 83.79 cm vs. 72.37 cm, respectively; $t = 3.781$, df = 214, $P < 0.001$). There was no significant difference in heights of low and high infestation trees for the second generation (mean = 96.49 cm vs. 92.46 cm, respectively; $t = 1.146$, df = 286, $P = 0.253$). The high late-season asynchrony, lower late-season efficacy, and lower late-season effect on tree height support the suggestion of Fettig et al. (2000b) that control efforts directed at the first generation may be the most economically advantageous for tip moth control.

This study shows that Nantucket pine tip moth developmental patterns can vary substantially even over a relatively small geographic area. Optimal spray dates in this region were early April to early May, mid-June to mid-July, and early to late August for each of three generations, respectively. In general, optimal spray dates at the Greensville Co. site, with a typical three generation tip moth phenology and high developmental synchrony, agreed most closely with those calculated by Fettig et al.

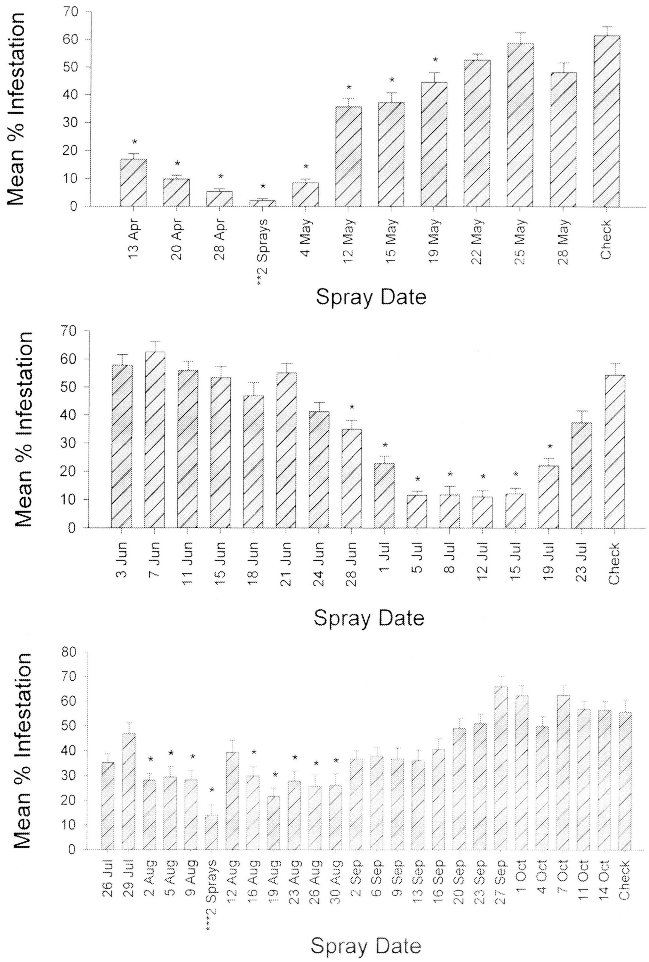

Fig. 6. Mean percentage infestation in plots treated with permethrin, April-May 1998 (top), June-late July 1998 (middle), and late July-October, 1998 (bottom). * = significantly less than check ($P < 0.05$, two-way ANOVA, Bonferroni *t*-test). ** = sprayed on 28 April and 15 May. *** = sprayed on 9 August and 30 August.

(2000a). Insecticidal treatments with permethrin can substantially reduce tip moth damage when applied during periods of peak egg and early-instar larval density. However, effectiveness is diminished when multiple cohorts produce tip moth populations with large numbers of insusceptible late-instar larvae present at any given time. Chemical control of tip moths using spray timing models, and assessment of control efforts, will likely be very difficult in areas with these anomalous developmental patterns.

Table 1. Optimal spray dates (degree-day accumulations in °C) for three tip moth generations based on peak combined densities of eggs and 1st instar larvae (Hertford Co., NC, Greensville Co., VA, and Isle of Wight Co., VA sites) or spray timing efficacy (Sussex Co., VA site)

	Location			
Generation	Hertford Co., NC	Sussex Co., VA	Greensville Co., VA	Isle of Wight Co., VA
First	8 May (353)	28 Apr (246)	9 Apr (157)	12 May (258)
Second	8 July (1112)	12 July (1139)	18 June (793)	5 July (1076)
Third	26 Aug (1924)	19 Aug (1709)	5 Aug (1518)	30 Aug (1914)

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