IMPACT OF PINE TIP MOTH ATTACK ON LOBLOLLY PINE

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

INTRODUCTION

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

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

METHODS

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

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

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

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

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

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

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

RESULTS AND DISCUSSION

Seasonal Tree Height Models

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

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

where

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

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

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

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

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

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

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

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

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

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

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

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

[a] IHT is the initial tree height (cm); FLUSH is the number of annual growth flushes; SITE1 and SITE2 are location (0 or 1); FAM1, FAM2, FAM3 and FAM4 is the pine family (0 or 1); TRT is the insecticide treatment (0 or 1); TI1, TI2 or TI3 are the tip moth infestation of the terminal (0 or 1) in generation 1, 2 or 3; PBI1, PBI2, and PBI3 are tip moth infestation in the top whorl (%) in generation 1, 2, or 3.
[b] $HT = b_0 + b_1 IHT + b_2 FLUSH + b_3 SITE1 + b_4 SITE2 + b_5 FAM1 + b_6 FAM2 + b_7 FAM3 + b_8 FAM4 + b_9 TRT + b_{10} TI1 + b_{11} TI2 + b_{12} TI3 + b_{13} PBI1 + b_{14} PBI12 + b_{15} PBI3$
[c] $HT = b_0 + b_1 IHT + b_{10} TI1 + b_{11} TI2 + b_{12} TI3$

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

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

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

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

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

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

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

Linking Seasonal Tree Height Models

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

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

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

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

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

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

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

Impact of Pine Tip Moth Attack on Loblolly Pine Volume

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

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

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

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

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

Economic Evaluation of Tip Moth Control

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

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

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

CONCLUSION

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

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

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

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

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