1984

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David Kulhavy
Arthur Temple College of Forestry and Agriculture, Stephen F. Austin State University, dkulhavy@sfasu.edu

Richard N. Conner
Wildlife Habitat and Silviculture Laboratory, Southern Research Station, U.S.D.A., Forest Service, Nacogdoches, Texas 75962

Mark White

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MARK N. WHITE,[1] DAVID L. KULHAVY, AND RICHARD N. CONNER[2]

School of Forestry, Stephen F. Austin State University, Nacogdoches, Texas 75962

Environ. Entomol. 13: 1598–1601 (1984)

ABSTRACT Twenty-two pine stands with a variety of site and stand characteristics and management strategies were analyzed using discriminant analysis to determine factors which influence Nantucket pine tip moth infestations. A whole-tree sequential sampling scheme designed to estimate absolute infestation rates (±5%) was used. An 8% infestation rate was used as the dividing line between high and low tip moth infestations. A sequential sampling program was used in the field to estimate populations. Absolute infestation rates ($\hat{P} \pm 5\%$), were obtained through random selection of pines for whole-tree sampling. Four equations were developed which gave 91% correct classification of initial data. The discriminating variables included site preparation intensity, pine height, pine age, site index, soil texture at 61 cm depth, depth of A horizon multiplied by soil texture code, and depth of clay.

THE NANTUCKET pine tip moth (NPTM), *Rhyacionia frustrana* (Comstock), is a serious pest of pine reforestation areas, seed orchards, ornamental pines, and Christmas tree plantations throughout the southern United States. Christmas trees and ornamental pines are affected in southern California (Yates et al. 1981). Larval feeding kills growing shoots by severing conductive tissue. Trees may be killed, but loss and retardation of growth upward and stem deformation are the most prevalent injuries.

Of the native southern pine species only shortleaf, *P. echinata* Mill., and loblolly, *P. taeda* L., pines are seriously damaged by NPTM attack in plantations. Virginia pines (*Pinus virginiana* Mill.) are particularly susceptible in Christmas tree plantations (Yates et al. 1981). Williston (1958) found height loss and mortality to be greater on shortleaf than on loblolly pines.

Site influences the severity of tip moth damage on host trees. Wakely (1928) observed that loblolly pines planted on sites best suited for longleaf pines were so seriously injured by NPTM damage they were overtaken by natural longleaf regeneration within ten years. Where outright tree-killing does occur by NPTM attack, pines are often growing on poor sites or under drought conditions (Flavell 1974).

Stand influences (pine height, age, density, and site preparation) are important in NPTM infestation rates. Pines planted after clear-cutting the residual forest result in higher rates of NPTM infestations than any other types of management; conversely, light over-story harvesting results in the lowest NPTM infestation. Fast growth upward tends to shorten the period of heavy NPTM attack (Lashomb and Steinhauer 1974). In general, tip moths infested more trees on the most intensively prepared sites where tree growth was better and competing vegetation was low; this infestation did not become serious until trees reached at least age 3 (Berisford and Kulman 1967, Flavell 1974, Hertel and Benjamin 1977). Yates (1966) states that high tree density reduces NPTM populations. Forestry trends, favoring the establishment of monoculture pine plantations, make the incidence of tip moth attacks an ever-increasing problem. The NPTM is becoming a pest of consequence on genetically improved seedlings in plantations with shorter rotations; as site preparation for pine plantation intensifies, the NPTM will increase in abundance (Flavell 1974).

Andersen (1980) modified Johnson's (1977) sequential program for sampling NPTM, and found only 2% difference between the average $\hat{P}$ for sequential sampling and systematic sampling. Andersen's scheme is a whole-tree system which gives an absolute tip moth infestation rate estimate ($\hat{P} \pm 0.05$), and it can be used to obtain accurate predictions of NPTM infestation rates within sample areas. Infestation rates obtained from his system can be used to develop a hazard rating system.

The objective of this research was to relate infestation rates of the Nantucket pine tip moth to site and stand factors in Nacogdoches County, Texas, in order to develop empirical hazard rating models.

[1] Current address: Texas Forest Service, Pittsburg, Tex.

[2] USDA Forest Service, So. For. Exp. Stn., Nacogdoches, Tex.

Materials and Methods

Twenty-two pine plantations in Nacogdoches County, representing 15 soil types, were located for sampling by aerial survey. Young pine plantations were photographed, sketch mapped, and located in the Nacogdoches County soil survey (Soil Conservation Service 1980). Exact boundaries were delineated and site numbers assigned. Suitability for sampling was determined by ground checking. Areas of at least 1 ha of pine vegetation type averaging less than 3 m in height were selected to represent a range of pine plantation management strategies. Most areas were plantations with an average age of less than 7 years. The approximate center of the soil type was confirmed by comparing a soil core to the description of the soil type.

The area of the soil type being sampled determined the maximum distance from center for plot establishment. A 0.004-ha plot was established and site and stand information were collected and coded. Site variables were derived from soil descriptions and profiles as described in the Nacogdoches County soil survey (Soil Conservation Service 1980) (Table 1).

The pine nearest to plot center was designated as a NPTM sample tree. The total number of tips on the tree (whole-tree sample) and the number of apparently infested tips were recorded. A tip was considered apparently infested if curling, resin flow, or death was observed. These values were entered into a sequential sampling program and the percentage of infestation rate calculated.

Plantations were sampled from late July through September to sample the maximum infestation rate of the tip moth (Andersen 1980). Plantations were sampled in both 1980 and 1981.

The sequential sampling routine developed for the programmable calculator by Johnson (1977) and modified by Andersen (1980) for field estimation of Nantucket pine tip moth populations allows the user to estimate infestation rates ($\hat{P}$) within preset bounds (B_E) on the error (i.e., $\hat{P} \pm 0.05$, $\hat{P} \pm 0.10$, etc.) at any desired confidence level. To do this, the standard error ($S_{\bar{x}}$) is calculated for the cumulative sample and multiplied by a constant (C) determined by the confidence level desired: 90% CL, $C = 1.64$; 95% CL, $C = 1.96$; 99% CL, $C = 2.58$. The resulting value (B) is compared to the preset bounds (B_E) during sampling and a termination decision reached when $B > B_E$. (Note: The value of $S_{\bar{x}}$ is determined by the value of P and the number of samples taken, as well as the total estimated number of sample units in the population—in this case, tips.)

If a decision was not reached, a new plot was located using a random distance (paces) and direction (eight ordinal compass directions) from the plot just completed and another pine selected for whole-tree sampling. This procedure was repeated and data entered into the sequential sampling program until a decision was reached. Once a decision

Table 1. Site and stand variables for hazard-rating young pine stands for *R. frustrana* infestation

Code	Variable
PEDON[a]	Code for the major soil component within the A horizon of a soil type. 1, Sand; 2, loam, 3, silt; 4, clay
SOCAT[a]	Code for soil texture within the A horizon. The code increases as soil texture becomes finer (see codes after SO61).
SO30[a]	Code for soil texture at 30 cm depth (see codes after SO61).
SO61[a]	Code for soil texture at 61 cm depth. 1, Fine sand; 2, loamy sand; 3, loamy fine sand; 4, sandy loam; 5, fine sandy loam; 6, very fine sandy loam; 7, sandy clay loam; 8, clay loam; 9, clay
SOLUM[a]	Depth (dm) of the soil profile in which active soil formation takes place. This is a measure of the depth of possible rooting activity. Highest = 20 dm, lowest = 8 dm
AHOR[a]	Depth of the mineral horizon at the surface of the soil profile. In this layer humified organic material is combined with mineral material. Highest = 12 dm, lowest = 1 dm
AHXSO[a]	Depth of A horizon (dm) (AHOR multiplied by soil texture code [SOCAT]). Highest = 40, lowest = 3
CLDEP[a]	Depth to clay layer or base of the soil profile if no clay layer is encountered. Highest = 243.8 cm, lowest = 0
SLOPE[a]	Average (%) incline of land surface from the horizontal. Highest = 20%, lowest = 0%
SI[a]	Site index (soil-derived) for loblolly pine at age 50. A measure of the height of loblolly pine planted on a site. Highest = 33.5 m, lowest = 16.8 m
THEC	Total number of pines per ha within the soil type being sampled (measured in 0.004-ha plots and compared to planting records). Highest = 16,917 trees/ha, lowest = 326 trees/ha
SOSOC	Code to indicate type of site preparation used and the length of time since site was prepared. Plantations were prepared by K-G blading and windrowing. This serves as a measure of vegetation control. 1, Pasture land (naturally seeded); 2, Naturally seeded pine area; 3, Site-prepared plantation, 0–1 years since prepared; 4, Site-prepared plantation, 1–4 years since prepared; 5, Site-prepared plantation, 4+ years since prepared
AGE	Average age (years) of pine on soil type being sampled. Obtained from either whorl count or planting records. Highest = 10 years, lowest = 2 years
HEIGHT	Average height (dm) of pines on soil type being sampled. Highest = 36 dm, lowest = 4 dm
RATE	Code for high/low infestation of Nantucket pine tip moths. A measure of percentage of tips attacked throughout the soil type being sampled. This variable was used for the actual classification of stands for discrimination. 1, ≥8% (High infestation) 2, <8% (Low infestation)

[a] Obtainable from Soil Survey of Nacogdoches Co., Tex. (Soil Conservation Service 1980).

Table 2. Discriminant function equations for site and stand relationships of NPTM, Nacogdoches County

1. $D^a = +0.79892(\text{SOSOC}) + 0.14840(\text{AGE}) + 0.06347(\text{SI}) - 8.77476$
2. $D = -0.90141(\text{SOSOC}) + 0.09991(\text{SI}) - 0.12681(\text{SO61}) - 0.32188$
3. $D = +0.73617(\text{SOSOC}) + 0.06917(\text{SI}) + 0.00785(\text{AHXSO}) - 8.468$
4. $D = +1.05285(\text{SOSOC}) - 0.08534(\text{HT}) + 0.37319(\text{AGE}) + 0.07665(\text{SI}) - 0.07308(\text{SO61}) - 10.44189$
5. $D = +1.16561(\text{SOSOC}) - 0.07554(\text{HT}) + 0.35610(\text{AGE}) + 0.10082(\text{SI}) - 0.34172(\text{SO61}) - 0.02260(\text{CLDEP}) - 10.07965$

Calculated values ≥0 are high-hazard sites for Nantucket pine tip moth (infestation ≥8%); calculated values less than 0 are low-hazard sites for tip moth (infestation <8%).

[a] Descriptions of coefficients are listed in Table 1.

was made ($\hat{P} \pm 0.05$) the crew returned to the soil type center to continue sampling. Field sampling continued in the sample area until a minimum of five decisions had been made.

From previous data (Andersen 1980) it was determined that a terminal leader infestation rate of 50% corresponded to a whole-tree rate of approximately 8% for the plantation. Therefore, all areas with infestation rates of 8% or more were coded as high-hazard, and areas less than 8% were coded as low-hazard with respect to NPTM infestations. Data for each area were assigned to the appropriate NPTM infestation rate code (high = 1, low = 2).

Discriminant function analysis (DFA) (Nie et al. 1975) was used to determine which site and stand factors discriminate between high and low infestation levels. Habitat variables were screened and five discriminant functions were derived which were used for stand classification. Pearson's correlation coefficients between the original variables and the discriminant axes for each variable were calculated (Hull and Nie 1979). These correlations can be used as a measure of discriminatory significance, removing all intervariable correlations, thus showing relative importance of each variable to all others. Once stand classification is complete, the developed equations can then be used for prediction of high or low NPTM damage and plantation hazard rating is possible.

Results and Discussion

Equation Development. Five DFA equations were derived for hazard-rating young pine plantations to the Nantucket pine tip moth (Table 2). These equations discriminate on a two-class (high or low) hazard around an 8% total tip infestation rate. The following site and stand variables were found to be the most important in discrimination (Pearson's correlation coefficients) (Hull and Nie 1979) (Table 3): SOSOC, site preparation code; SI, site index of loblolly pine (ft) (soil derived, age 50); AGE, age as derived from tree ring count or planting records; HT, height of trees in decimeters; AHXSO, depth of A horizon (AHOR) times soil texture code; and SO61, soil texture codes at 61 cm. These variables (along with CLDEP, depth to clay or the maximum rooting depth) were most important in the stepwise DFA for development of usable discriminant equations. CLDEP, a poor discriminator, was included in the fifth equation giving 100% correct classification of the data used to develop the classification (Table 2).

The foregoing variables in the five equations permit discrimination between high and low hazard of NPTM infestations, are satisfactory in ease of data collection, and provide forest managers with guidelines for identification of sites where NPTM may become a problem.

Equations and Their Applicability. Equation 1 (Table 2) discriminated between high and low infestations using the variables SOSOC, SI, and AGE (Table 2). Site preparation intensity was the most discriminatory variable in DFA 1. In high-hazard areas, care should be taken not to remove all ground cover. Site index, a reflection of growth potential, is important in identifying areas at high risk of NPTM infestation. Areas of high site index may be best suited to other than clear-cutting pine management techniques. Other regeneration methods or tree species may be better suited if NPTM will pose a probable economic loss. AGE is the least discriminating. As stand age increases, tip moth infestation rates increase. A 91% correct classification was obtained using this equation.

Equation 2 (Table 2) was developed for managers not having available planting information or who may be planning a future plantation. This equation is keyed to site variables obtainable from a soil survey. Site preparation (SOSOC) and site index (SI) are the most discriminating variables; the third (SO61) is less discriminating but is significant ($P < 0.05$). As soil particle size increases, NPTM hazard increases; sandy textures increase site hazard.

In equation 4 (Table 2), variables from equations 1 and 2 were combined with height data collected during field examinations. NPTM infestations are negatively correlated with height, indicating that pines grow out of NPTM susceptibility. The magnitude of the Pearson correlation coefficient (Table 3) indicates that AGE is a better discriminator than height. This equation, with a 91% correct classification, may be used in existing plantations to monitor tip moth infestations.

Equation 5 (Table 3) is included since it gave a 100% correct classification of the 22 stands sampled. Included is the variable CLDEP (depth to clay [dm] or base of the A soil horizon). CLDEP is easy to derive from a soil survey, so equation 5 is comparable in use to equation 3. The correlation of CLDEP shows the variable as a very poor discriminator (Table 3); further sampling will be required to verify its usefulness.

Use of Discriminant Function Analysis Equa-

Table 3. Correlations of variables to axes for equations in Table 2

	SOSOC	SI	AGE	SO61	AHXSO	HT	CLDEP
Equation 1	+ 0.612	+ 0.502	+ 0.366				
Equation 2	+ 0.540	+ 0.483		+ 0.163			
Equation 3	+ 0.634	+ 0.463			+ 0.052		
Equation 4	+ 0.420	+ 0.344	+ 0.251	+ 0.116		+ 0.143	
Equation 5	+ 0.376	+ 0.308	+ 0.225	− 0.104		+ 0.125	− 0.020

tions for Classification of Pine Stands to NPTM Susceptibility. Equations 1, 4, and 5, incorporating site and stand variables, are suitable for rating existing plantations. Equation 1 is stand based on age and site preparation; with a soil survey and planting records field work is minimized. Equations 2 and 3 are based on site index, SO61, and AHXSO. They supply area hazard guides; equations utilizing stand (i.e., age, height) variables should be substituted after pines are planted. Information required for equations 2 and 3 can be obtained from the soil survey.

These equations were developed for the forest manager for ease in application and accuracy in prediction. The entire system was developed for Nacogdoches Co., Tex., and is currently being tested in adjacent counties. Hazard-rating for NPTM based on percentage of infestation was accomplished using a sequential sampling scheme developed by Andersen (1980). This system was fast and accurate for obtaining absolute infestation rates over a large area within a few hours. As the objective was to estimate infestation rates (as measured by infested shoots), more precise estimators of populations (e.g., Garguillo and Berisford 1981, Garguillo et al. 1983) were not required. Managers needing to sample frequently would find the system economical with a minimum of sampling. These relationships of NPTM to site and stand conditions show that forest managers should consider these variables when selecting plantation sites. In general, tip moth infestations were greatest on plantation sites with higher site indexes in plantations prepared by bulldozing with a K-G blade and windrowing. Other site preparation methods (e.g., roller chopping) were not examined. However, Hertel and Benjamin (1977) stated greater intensity of site preparation increased tip moth infestations. Older plantations (up to age 10) had higher infestation rates, but this was moderated by height.

The DFA equations developed may be used to categorize areas before planting to anticipate those areas that may require remedial control efforts. Plantations already established can be rated for their current expected tip moth populations.

Acknowledgment

We gratefully acknowledge Paul C. Johnson for his critical review of the manuscript. Research supported by McIntire-Stennis funds and a Sigma Xi grant.

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Received for publication 2 March 1984; accepted 25 July 1984.