[The Great Lakes Entomologist](https://scholar.valpo.edu/tgle)

Volume 17
Number 3 - Fall 1984 *Number 3 - Fall 1984*

Article 9

October 1984

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Ann M. Lynch
University of Michigan

Gary W. Fowler
University of Michigan

John A. Witter
University of Michigan

Recommended Citation

Lynch, Ann M.; Fowler, Gary W.; and Witter, John A. 1984. "Development of Empirical Models to Rate Spruce-Fir Stands in Michigan's Upper Peninsula for Hazard From the Spruce Budworm (Lepidoptera: Tortricidae): A Case History," *The Great Lakes Entomologist*, vol 17 (3)
DOI: https://doi.org/10.22543/0090-0222.1512
Available at: https://scholar.valpo.edu/tgle/vol17/iss3/9

DEVELOPMENT OF EMPIRICAL MODELS TO RATE SPRUCE-FIR STANDS IN MICHIGAN'S UPPER PENINSULA FOR HAZARD FROM THE SPRUCE BUDWORM (LEPIDOPTERA:TORTRICIDAE): A CASE HISTORY

Ann M. Lynch, Gary W. Fowler, and John A. Witter[1]

ABSTRACT

The procedure used to develop empirical models which estimate potential spruce budworm impact to spruce-fir stands in Michigan's Upper Peninsula is reviewed. Criteria used to select independent variables, to select the best of alternative multiple linear regression models, and to validate final models are discussed. Preliminary, intermediate, and final results demonstrate a cyclic pattern to the development procedure. Validation is emphasized as an important step in the procedure. Implications of using the hazard-rating system as a pest management tool in the stand management process are discussed.

Management of the spruce budworm, *Choristoneura fumiferana* (Clemens), in forest situations in the Lake States has emphasized cultural methods. Chemical and microbial insecticides have been used occasionally in recent years on high value spruce, fir, and eastern hemlock trees in campsites, seed orchards, Christmas tree plantations, and research plots. However, silvicultural management methods are usually the only techniques used in most spruce-fir stands in Michigan's Upper Peninsula. Techniques include clearcut harvest of relatively pure balsam fir and white spruce stands before they become overmature; strip, block, and shelterwood cuttings; mixed-species, uneven-aged management; salvage of impacted stands; and pre-salvage of vulnerable stands (Flexner et al. 1983).

Poor market demand for spruce and fir in the Upper Peninsula has strongly influenced the effectiveness of silvicultural management due to the dependency on harvesting. Where and when feasible, preventive management has occurred and has been effective. For example, impact in the central portion of Michigan's Upper Peninsula has been considerably less than in the eastern portion of the peninsula (1.1 vs. 5.6 m^2/ha dead balsam fir basal area) (Lynch and Witter 1983a,b). This difference is due, at least in part, to relatively high demand for and consequent heavy harvest of spruce and fir in the central area. Demand in this area has been influenced by the presence of a pulp mill at Escanaba. The expansion and addition of pulp mills in the Upper Peninsula has recently improved the local market demand for spruce and fir. Forest managers throughout the Upper Peninsula have recently been in a better position to control or prevent spruce budworm impact.

When prevention, as opposed to remedial control, is emphasized in pest management programs the prediction of when, where, and how much impact will occur is essential. Predicting when impact will occur is usually done through pest population prediction or after the fact. Identifying where and how much impact will occur is the function of hazard-rating systems. Hazard-rating systems may be empirical or mechanistic in nature, and are often based upon a good understanding of pest population behavior and ecosystem interactions (Hedden 1981).

[1]School of Natural Resources, The University of Michigan, Ann Arbor, MI 48109.

No quantitative hazard-rating system for the spruce budworm has been available for Michigan. The objectives of this paper are to review the development of our stand hazard-rating system for Michigan's Upper Peninsula, document intermediate and final results, and discuss the development of pest management decision-making models in general.

GENERAL APPROACH

The development of the hazard-rating system was one objective of a long-term (7-year) integrated study on the impact of the spruce budworm on spruce-fir stands in Michigan's Upper Peninsula (Witter and Mog 1981). The objective of the hazard-rating system was to assist forest managers in reducing forest vulnerability to the spruce budworm. This system would help managers select areas which require prevention or protection strategies, schedule presalvage and salvage operations, and plan preventive harvest operations. We set the following general guidelines for the system: (1) the system would be quantitative rather than qualitative, i.e., based on analytical measurements and models, (2) the parameters would be commonly assessed in most forest inventory systems, (3) the system would be designed to be easily integrated into forest management plans, and (4) the statistical model(s) developed would have biological meaning in addition to statistical significance.

The original procedure planned for the development of the hazard-rating system was relatively simple: (1) use data collected during 1978–81 from a permanent plot system to develop an empirical, quantitative predictive model or models, (2) collect an independent data set from additional stands in 1981 and use it to validate the model(s), (3) make any indicated refinements, and (4) implement the predictive model(s) in the form of a hazard-rating system. The actual model building procedure followed a much more involved sequence of events. Validation of developed models resulted in numerous subsequent revisions and returns to the development stage, until the procedure evolved into a cyclic pattern (Fig. 1).

STATISTICAL APPROACH

Data were collected from 68 stands in the Michigan Impact Plot System (MIPS) (Mog and Witter 1979, Mog et al. 1982). This permanent plot system is located in the Ottawa National Forest (N.F.) and the Hiawatha N.F. (Fig. 2). The sampling design used was stratified three-stage cluster sampling with two plots per stand. Data included the following parameters for all tree species: average tree diameter, average crown position, number of live trees per hectare, and live basal area per hectare. Height and crown length measurements were taken for spruce and fir species. Impact parameters assessed for spruce and fir species included dead basal area per hectare, the number of dead trees per hectare, percent mortality (by stem count), and percent basal area mortality. Site parameters pertaining to drainage, topographic position, and soil type were evaluated. Each plot was placed into a site classification unit according to a preliminary classification system presented by Witter (1981). Soil samples were collected and later analyzed in the laboratory.

The multitude of parameters which were assessed (Table 1) for several species (Table 2) were screened for subsequent analysis by one or more of the following standards: (1) correlation coefficients, *r*, were used to measure the strength of linear relationships between impact variables and stand, site, and soil variables, (2) scatter graphs were used to search for nonlinear relationships, (3) variables were screened for relevant biological significance, and (4) variables that limited the number of observations below a usable limit were discarded. For example, diameter of an infrequently occurring species, such as eastern white pine, obviously restricted further analysis to those few stands where that species was present. Certain variables were not suitable for an operational decision-making system, such as laboratory determined soil parameters. However, inclusion of

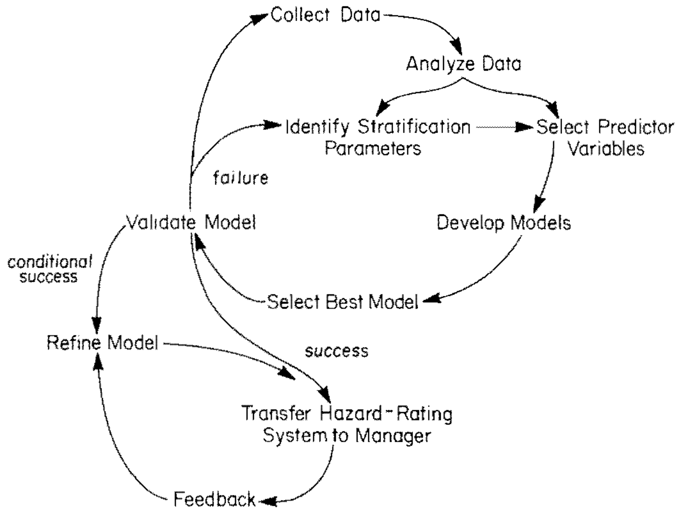

Fig. 1. Schematic representation of the sequence of events in the model building procedure.

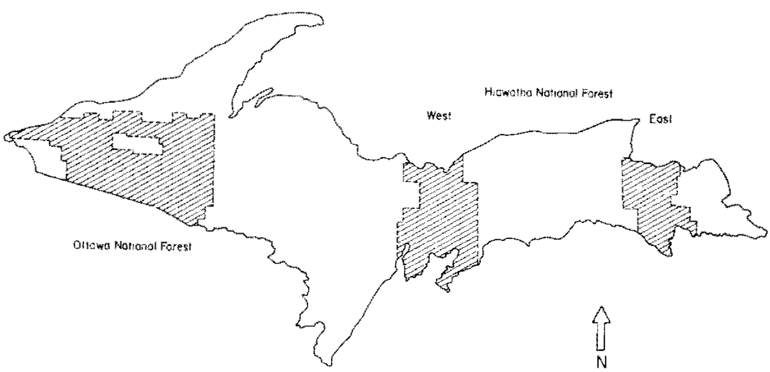

Fig. 2. The Upper Peninsula of Michigan, showing the location of the Ottawa and Hiawatha N.F.

these variables during preliminary analyses helped us to more thoroughly understand the interactions between the site, stand, and pest. Such variables were eliminated during later stages of system development.

The variables chosen were entered into a stepwise regression procedure. The criteria selected to judge the "best" regression models included real-world (biological) meaning, maximization of the coefficient of multiple determination (R^2), maximization of the F-ratio, minimization of the standard error of the estimate (SEE), and minimization of model complexity, i.e., as few variables as possible to develop a satisfactory model. The regression assumptions of normality and equal variance were tested only on final models.

Preliminary validation involved examining the errors (residuals) of the predicted impact values relative to the observed values. Models with excessively large error terms or

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Table 1. Variables evaluated in the analyses, with labels.

Label	Variable
	Impact variables for spruce and fir species
BA%D.XX	Percent basal area mortality of species XX
DBA.XX	Dead basal area of species XX (m^2/ha)
DNT.XX	Number of dead trees per ha of species XX
MORT.XX	Percent tree mortality of species XX
	Stand variables
BA.XX	Live basal area (m^2/ha) of species XX
BA%XX	Proportion of total basal area that is species XX
CP.XX	Average crown position rank of species XX: 1 = dominant, 2 = codominant, 3 = intermediate, 4 = suppressed
DBH.XX	Average diameter (cm) of species XX
HT.XX	Average height (m) of species XX, spruce and fir only
NT.XX	Number of live trees per ha of species XX
NT%XX	Proportion of trees that are species XX
YN.XX	Dummy variable for presence of species XX: 1 = no, 2 = yes
	Site variables
AGE	Average age of spruce and fir
ASPECT	Aspect
DRAINAGE	Drainage class: moderate, somewhat poor, poor
DRYWET	Categorizes drylands in general dryland areas, drylands surrounded by wetlands, and wetlands
GRNDWTR	Depth to ground water
HA	Hectares
MOTTLNG	Depth to soil mottles
POSITION	Position on a slope: upper-slope, mid-slope, lower-slope or flat
RANGE	Stand position on east-west gradient. Value used is U.S. public-land survey range, with respect to the principal meridian
SLOPE%	Percent slope
SOIL	Light vs. heavy mineral soil
SOILDPTH	Depth of soil: deep vs. shallow
SOILTYPE	Field determination of soil type: mineral vs. organic
TERRAIN	Categorical descriptions of general topography
TEXTURE	Broad texture categories: mineral soils only: sand, loam, clay, silt
	Soil variables
CLAY	Proportion of mineral soil that is clay
CSAND	Proportion of sand fraction that is coarse
FSAND	Proportion of sand fraction that is fine
MSAND	Proportion of sand fraction that is medium
pH	Soil pH
SAND	Proportion of mineral soil that is sand
SILT	Proportion of mineral soil that is silt
VCSAND	Proportion of sand fraction that is very coarse
VFSAND	Proportion of sand fraction that is very fine

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DOI: 10.22543/0090-0222.1512

Table 2. Tree species evaluated in the analysis.

Label	Common, scientific name
AE	American elm, *Ulmus americana* L.
AH	Ash, *Fraxinus* spp., mostly *F. nigra* Marsh., but also *F. americana* L. and *F. pennsylvanica* Marsh.
AP	Aspen, *Populus grandidentata* Michx., *P. tremuloides* Michx., and *P. balsamifera* L.
BC	Black cherry, *Prunus serotina* Ehrh.
BE	American beech, *Fagus grandifolia* Ehrh.
BF	Balsam fir, *Abies balsamea* (L.) Mill.
BI	Yellow birch + paper birch
BS	Black spruce, *Picea mariana* (Mill.) B.S.P.
EL	Eastern larch, *Larix laricina* (Du Roi) K. Koch
HE	Eastern hemlock, *Tsuga canadensis* (L.) Carr.
HW	Hardwoods
JP	Jack pine, *Pinus banksiana* Lamb.
OK	Oak, *Quercus* spp.
PB	Paper birch, *Betula papyrifera* Marsh.
RM	Red maple, *Acer rubrum* L.
RP	Red pine, *P. resinosa* Ait.
SF	Spruce + balsam fir
SM	Sugar maple, *A. saccharum* L.
SP	Black + white spruce
T	Total of all species
WC	Northern white-cedar, *Thuja occidentalis* L.
WS	White spruce, *P. glauca* (Moench) Voss
WP	Eastern white pine, *P. strobus* L.
YB	Yellow birch, *B. alleghaniensis* Britton

systematic errors were discarded or refined. An additional, independent data set was then used for further validation. Model validity was based on management as well as statistical criteria since the objective was to develop a system for operational use by forest managers. Impact estimates were calculated using the values of the predictor variables observed in the independent data set. Predetermined limits were set for the errors of the calculated impact values. Limits were dependent upon the magnitude of the observed impact values for the strata under consideration. Statistical validation criteria included the correlation of predicted and observed values, stability of the variables' coefficients with independent data, and tests of significance and goodness-of-fit. The errors of the predicted values were examined for systematic trends. A model that failed to pass rigorous statistical tests was not necessarily eliminated from consideration. Such a model might be more suitable for management objectives than a more statistically valid one. For example, a model may exhibit some consistent bias which causes it to fail goodness-of-fit tests. If this bias is conservative, the model may still be useful for management purposes (Welch et al. 1981).

We hope that the general approach and statistical procedures described give Michigan forest managers a simple, analytical system to estimate the level of impact that might occur in individual spruce-fir stands during a spruce budworm outbreak.

RESULTS

Preliminary Analysis

Our original analyses were designed to predict the combined impact of the spruce budworm on the three major hosts that occur in the Upper Peninsula: balsam fir, white spruce, and black spruce. Impact was quantified as DBA.SF, BA%D.SF, and MORT.SF (see Tables 1 and 2 for abbreviations). Predictor variables were selected and linear models developed as described.

Analysis of the 1980 data from the MIPS indicated that the amount of variation in the data was exceedingly large, in terms of both the impact and the predictor variables. The "best-case" regression model explained only 23% of the variation in the impact variable DBA.SF (Table 3). Major differences existed between the relationships observed in the Ottawa N.F. and the Hiawatha N.F., so separate models were developed for each national forest (Fig. 2). This stratification improved the predictive abilities of the analysis, but only 40% of the variation in DBA.SF in the Ottawa N.F., and 45% of the variation in BA%D.SF in the Hiawatha N.F. could be accounted for (Table 3). One difficulty was that stratification of the data set by variables such as national forest or the presence-absence of a particular species resulted in insufficiently large sample sizes for model development. In addition, impact in the Ottawa N.F. may have been too light to adequately distinguish stands with low hazard from stands with high hazard. The budworm outbreak was more advanced in the east than in the west (Hastings and Mosher 1976). Non-host species appeared to be important indicators of site vulnerability, particularly northern white cedar, red maple, sugar maple, yellow birch, and paper birch.

We proceeded to analyze the stand, site, and soil data in detail with the intent of identifying meaningful strata, to remeasure the MIPS stands in 1981, and to collect stand data on additional stands in order to increase the sample size.

Detailed Analysis of 1981 MIPS Data

The detailed data collected during the establishment of the MIPS were analyzed to study the association between stand, site, and soil characters and impact from the spruce budworm. Correlation and principal component analyses were used to identify factors associated with the variability in the stands and impact on balsam fir. This analysis was presented in detail by Lynch (1984). Factors which appeared to influence variability were (1) the quantity of balsam fir present in the stand prior to the outbreak, (2) stand species composition, (3) site factors, particularly those indicative of soil moisture availability, (4) the length of time the outbreak had been in progress in different parts of the peninsula, and (5) random biological variability. Variables concerning infrequently occurring species (oak, beech, black cherry, American elm, basswood, ash, jack pine, red pine, white pine, and in the Hiawatha N.F., eastern larch) greatly contributed to the total variability in the data matrices and had undesirably important influences in the analyses.

Based on these results, the data were stratified by soil type (organic or mineral), geographic region (east or west, i.e., Ottawa N.F. or Hiawatha N.F.), and by the

Table 3. Preliminary models developed from 1980 MIPS data to predict impact on spruce and fir.

Total sample, $n = 68$

$$DBA.SF = -11.75 + 2.36\ YN.WC + 0.74\ DBH.SF + 1.78\ YN.BI$$

$$R^2 = 0.230 \quad SEE = 3.380 \quad F = 6.385 \quad \text{Sig.} = 0.0007$$

Hiawatha N.F., $n = 26$

$$DBA.SF = -0.41 + 0.21\ NT\%SF + 0.27\ YN.BI + 0.001\ NT.RM$$

$$R^2 = 0.453 \quad SEE = 0.241 \quad F = 6.062 \quad \text{Sig.} = 0.0036$$

Ottawa N.F., $n = 41$

$$DBA.SF = -0.06 + 0.86\ NT\%WC + 0.02\ DBH.BF - 0.11\ YN.SP - 0.10\ YN.SM$$

$$R^2 = 0.398 \quad SEE = 0.137 \quad F = 5.947 \quad \text{Sig.} = 0.0009$$

proportion of balsam fir basal area present. We restricted further analysis to balsam fir impact, rather than spruce and fir combined, in order to reduce the variability. Study of white spruce and black spruce impact would proceed as separate studies. Independent variables pertaining to the infrequently occurring species were eliminated.

Development of Empirical Models for Each Stratum

Stand parameters were sampled in an additional 82 stands in 1981, for a total of 150 stands. A random 2-stage cluster sampling design was used, with three plots per stand. All variables were measured on 0.04-ha plots, except height and crown measurements which were measured on 0.02-ha plots. Three 0.04-ha plots more accurately and precisely estimate impact parameters than either two 0.04- or two 0.08-ha plots (Karpinski and Witter 1982).

Limiting the impact parameters to balsam fir and stratification of the data set by soil type and geographic region greatly improved the precision and accuracy of the analysis. When the data were further stratified by the proportion of the stand that was balsam fir, the stratum with greater proportions of balsam fir was much less variable than the strata with small proportions of balsam fir. Suitable models could not be developed for the latter strata, so stratification by BA%BF was abandoned.

Three linear models were developed to predict spruce budworm impact:

[1] **Hiawatha N.F. stands on mineral soils.**

$$\text{DBA.BF} = -48.3 + 0.141\ \text{NT\%BF} + 2.378\ \text{DBH.BF} - 0.183\ \text{BA.T} + 8.695\ \text{YN.WC}.$$

$R^2 = 0.636$, $SEE = 3.660$, $F = 6.64$, $p = 0.003$, $n = 20$.

[2] **Ottawa N.F. stands on mineral soils.**

$$\text{DBA.BF} = 0.551\ \text{BA.BF} - 0.007\ \text{NT.BF} - 0.515\ \text{BA.WC} + 0.030\ \text{NT.WC}.$$

$R^2 = 0.558$, $SEE = 1.733$, $F = 63.137$, $p < 0.000$, $n = 70$.

[3] **Stands on organic soils.**

$$\text{DBA.SF} = -5.498 + 0.011\ \text{NT.SF} - 0.051\ \text{NT\%SF} - 0.129\ \text{BA.BF} + 0.355\ \text{DBH.BF}.$$

$R^2 = 0.589$, $SEE = 6.503$, $F = 14.305$, $p < 0.001$, $n = 25$.

Validation and Refinement

Stands on mineral soils in the Hiawatha N.F. Twenty-five stands in the Hiawatha N.F. sampled in the 1981 supplementary sample were used for validation of model [1]. DBA.BF values were predicted using the values of NT%BF, DBH.BF, BA.T, and YN.WC observed in the independent sample. Results were not satisfactory, with low correlation between the observed and predicted values of DBA.BF ($r = 0.30$). The prediction errors were far too large, with only 28 and 40% of the predicted values within 1 and 2 m^2/ha, respectively, of the observed values. Examination of the error terms indicated the following trends: (1) the largest errors were over-predictions of DBA.BF, (2) DBA.BF was usually over-predicted when YN.WC had a value of 1 (no northern white cedar present on site), and (3) the error values for stands in the western portion of the Hiawatha N.F. were always negative or close to zero, but the values for the eastern portion were randomly positive and negative (Fig. 3). This systematic bias in the error terms appeared to be caused by differences in the amount of impact between the eastern and western regions of the Hiawatha N.F. (5.6 vs. 1.1 m^2/ha DBA.BF). An additional problem with this model was that the *y*-intercept coefficient, −48.3, was an unrealistic

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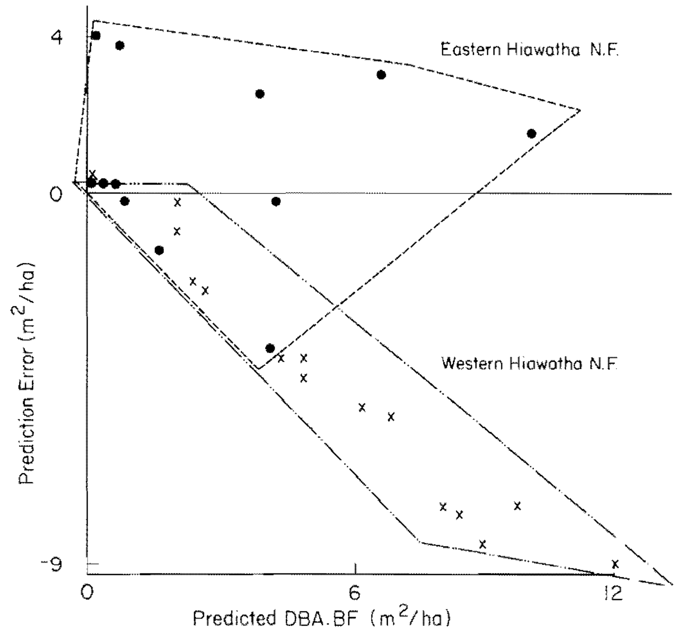

Fig. 3. Prediction errors from model [1], showing systematic bias with geographic area.

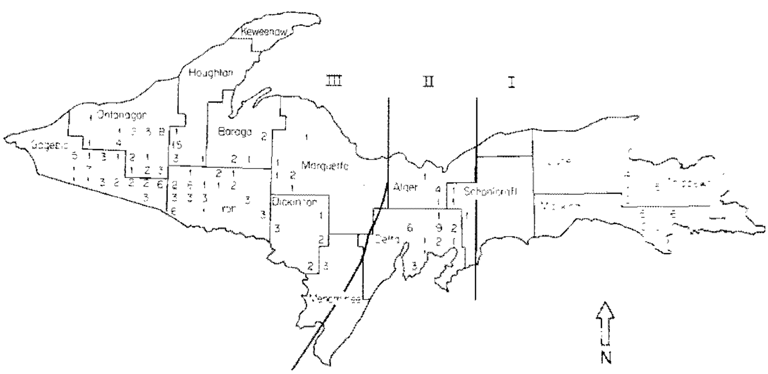

Fig. 4. The Upper Peninsula of Michigan, showing county boundaries, the location of sampled stands, and the three geographic regions used as strata.

value since it infers extreme negative mortality. Based on these results, we decided to model the eastern area of the national forest separately from the western area.

The model used to predict impact in the eastern region of the Hiawatha N.F. (Region I, Fig. 4), was developed from 12 stands in the Michigan Impact Plot System. The function chosen to predict impact in stands on mineral soils in the eastern Upper Peninsula was

[4] DBA.BF = 1.009 + 0.868 BA.BF − 0.081 BA%AP.

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DOI: 10.22543/0090-0222.1512

The model was significant ($F = 20.95, p < 0.005$), with $R^2 = 0.823$ and $SEE = 2.306$. The model validated well against 12 stands from the 1981 supplementary sample. The predicted and observed values of DBA.BF were highly correlated ($r = 0.95, p < 0.01$). Eleven of the predicted values were within 2 m²/ha of the observed values. No DBA.BF was observed in the remaining stand and the model predicted 3.1 m²/ha. The original and validation data sets were pooled to obtain the final model:

[5] DBA.BF = 0.116 + 0.906 BA.BF − 0.061 BA%AP,

which was significant ($F = 96.78, p < 0.005$) with $R^2 = 0.902$ and $SEE = 1.740$.

The best model to predict impact in the western region of the Hiawatha N.F., developed from 14 stands in the MIPS sample, was

[6] DBA.BF = 0.697 + 0.0003 NT.BF − 0.170 BA.SP.

The model was significant ($F = 12.94, p < 0.0002$), with $R^2 = 0.702$ and $SEE = 1.195$. However, validation against 21 stands in the supplementary sample was inadequate. The predicted and observed values of DBA.BF were not significantly correlated ($r = 0.255$, $p > 0.10$). Predicted values were systematically larger (70–540%) than the observed values.

Stands on mineral soils in the Ottawa N.F. An independent data set was obtained in 1982 for validating model [2] from 50 stands on lands belonging to Champion International Corporation. A random 2-stage cluster sampling design with three plots per stand was utilized. Again, the validation attempts failed. Correlation between the observed and predicted values was low, although statistically significant ($r = 0.564, p < 0.01$). Predicted values were systematically larger than the observed values, by as much as 6 m²/ha DBA.BF. When the data from the validation sample were used to derive new coefficients for the dependent variables, the coefficients changed considerably and only 38% of the variation in DBA.BF was explained.

Stands on organic soils. Because so few wetland sites were sampled, model [3] was not validated. We hesitated to interpret the relations between impact and the variables in this model. There is little information available concerning the interactions between the spruce budworm and spruce-fir trees on wetlands. However, impact patterns on wetlands very clearly differ from impact patterns on mineral soils (Lynch 1984). We do not encourage the use of model [3] in forest management decision processes because the ecological implications of the variables included in the model are not clear, and because we did not validate the model.

Repeating the Development Cycle

At this point we combined the data from all stands on mineral soils, exclusive of those in Region I (Fig. 4). Twenty-five percent of the combined sample was randomly selected and set aside for validation purposes. We examined the potential of stratifying the data according to (1) the presence-absence of different species, (2) further geographic division, and (3) the basal area of balsam fir.

Species stratification. Strata pertaining to the presence or absence of individual species that earlier analyses indicated might contribute to the variability of impact were examined. These species were aspen, paper birch, red maple, sugar maple, northern white cedar, black spruce, and white spruce. Usually, a successful model could be developed for one stratum but not the other. For example, the function

[7] DBA.BF = −0.544 + 0.008 NT.BF − 0.004 NT.AP + 0.007 NT.WC

explained 78% of the variability in DBA.BF for 31 stands in which red maple *was not* present. However, the best model developed for 66 stands where red maple *was* present explained only 45% of the variation in DBA.BF:

[8] DBA.BF = −3.11 + 0.214 BA.BF + 0.412 BA.SM
−0.303 NT%SM + 0.084 RANGE.

Geographic stratification. Stratifying the stands located in the central area of the Upper Peninsula (Region II, Fig. 4) apart from those in the western area greatly reduced the variability of the remaining sample. As described earlier, impact in this area has been greatly influenced by pre-salvage and salvage of spruce-fir stands. Twenty-four stands were sampled in this region, and their DBA.BF ranged from 0.0 to 4.8 m^2/ha, with a mean ($\pm SE$) of 1.0 $\pm$ 1.2 m^2/ha. Twenty-one of these stands had lost less than 2.0 m^2/ha of balsam fir basal area. Because the observed impact was consistently low we decided to express potential impact in this region as the mean value observed ($\pm SE$). Impact patterns may have been similar to those in the eastern portion of the peninsula without human influence.

Quantity of balsam fir stratification. Stratifying the remaining sample by the *amount* of pre-outbreak balsam fir basal area present was more successful than our earlier attempts to stratify by the *proportion* of the stand basal area in balsam fir. We studied the effect of defining strata class limits at 0–6, 0–8, 0–10, 6–10, 6+, 8+, and 10+ m^2/ha of BA.BF. Stratifying the sample into stands with greater or less than 10 m^2/ha was most successful.

The function chosen to predict impact in stands in Region III (Fig. 4) with at least 10 m^2/ha of BA.BF was

$$[9]\ \text{DBA.BF} = 0.255\ \text{BA.BF} - 0.154\ \text{NT\%BF} + 0.270\ \text{RANGE}.$$

The model, developed from 41 stands, was significant ($F = 60.94, p < 0.005$) with $R^2 = 0.556$ and $SEE = 1.627$. Although only 56% of the variation was explained by this model, it had relatively good predictive capabilities. The DBA.BF values predicted for the validation stands were within 2 m^2/ha for nine out of 12 stands. The remaining three predictions were within 3 m^2/ha of the observed values. The two samples were pooled to obtain a final model:

$$[10]\ \text{DBA.BF} = 0.362\ \text{BA.BF} - 0.180\ \text{NT\%BF} + 0.267\ \text{RANGE},$$

which was significant ($F = 89.34, p < 0.005$) with $R^2 = 0.580$ and $SEE = 1.561$.

There were 81 stands on mineral soils in Region III which had less than 10 m^2/ha of balsam fir basal area present prior to budworm attack. They incurred very little impact, with a mean DBA.BF ($\pm SE$) of 1.3 $\pm$ 1.6 m^2/ha. We were unable to explain more than 50% of the variation in DBA.BF with a (reasonable) model. Because less than 50% of the variation could be explained and because the observed impact was consistently low, we decided to express potential impact as the mean value observed ($\pm SE$).

The Hazard-rating System

The final hazard-rating system estimates potential impact to balsam fir in stands on mineral soils located in Michigan's Upper Peninsula (Lynch 1984). Linear models that estimate potential impact were developed and validated for three geographic regions (Fig. 4). Potential dead balsam fir basal area in the eastern Upper Peninsula (Region I) was estimated as a function of pre-outbreak balsam fir basal area and the percent stand composition in aspen using model [5]. The mean ($\pm SE$) dead balsam fir basal area per ha was used to estimate potential impact in the central portion of the peninsula (Region II). Model [10] was used to estimate dead balsam fir basal area in stands in the western Upper Peninsula (Region III) with at least 10 m^2/ha of balsam fir basal area as a function of pre-outbreak balsam fir basal area, percent stand composition in balsam fir, and stand position on an east-west gradient (Range). The mean ($\pm SE$) dead balsam fir basal area per ha was used to estimate potential impact in stands in Region III with less than 10 m^2/ha of balsam fir basal area.

DISCUSSION AND CONCLUSIONS

Estimates from models [5] and [10] and the two mean values can be used by forest managers to rank stands for vulnerability to the spruce budworm. Stands can be classified for preventive, pre-salvage, and salvage harvest operations or for remedial treatments. The system should be easily implemented because the necessary data are readily available from routine compartmental examinations and inventory systems.

When presenting this information to forest managers, we emphasize that their decisions should be based on relative, rather than absolute, estimates of impact. Stands can be indexed or ranked according to estimated losses. The relative hazard rank is one decision criterion or component of the entire stand management program. We believe that the hazard-rating system will provide forest managers with a useful management tool. Pest management models assist managers in making decisions, but should not make absolute decisions for the land manager. Many other factors influence the decision process. Pest management is but one aspect of forest management, and rating systems are but one tool available in pest management programs.

Our study clearly illustrates the importance of validating pest management decision models. The development of the hazard-rating system followed a cyclic pattern of data collection, analysis, validation, and refinement. New information and understanding of the ecological system was gained at each step. Without validation, the probability of making erroneous decisions with the rating system would have been considerably greater. We have much more confidence in the quality of the final system than in the preliminary models developed. Of course, the ultimate test of the hazard-rating system will be its performance in actual use. Model validation should be a continuing process of feedback and modification (Fig. 1). Validation procedures for pest management models are discussed by Hedden (1981) and Welch (1981).

ACKNOWLEDGMENTS

We acknowledge important contributions to this study from B. V. Barnes, D. M. Hix, C. Karpinski, Jr., T. P. Mog, and B. A. Montgomery. The cooperation and assistance of personnel of the U.S. Forest Service, Ottawa and Hiawatha National Forests, and of Champion International Corporation is gratefully acknowledged. Work leading to this publication was funded in part by a Canada-United States Spruce Budworms grant, by McIntire-Stennis funds, and by The University of Michigan.

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DOI: 10.22543/0090-0222.1512