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Tree mortality risk of oak due to gypsy moth

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Summary

We present prediction models for estimating tree mortality resulting from gypsy moth, *Lymantria dispar*, defoliation in mixed oak, *Quercus* sp., forests. These models differ from previous work by including defoliation as a factor in the analysis. Defoliation intensity, initial tree crown condition (crown vigour), crown position, and species grouping classes were highly significant in categorical analysis of variance for mortality. Heavy defoliation intensity was shown to have a strong, consistent influence in increasing the probability of tree mortality. Classification and Regression Tree (CART) analysis, a binomial decision tree procedure, was used to develop prediction models of mortality risk for use by forest managers. The best decision tree had 65 groups that correctly classified 75% of the live trees and 76% of the dead trees. Models were run separately by defoliation class and provided correct classifications between 63 and 78% of the trees. Forest land managers can use these models to assign probabilities of death for moderate and heavy defoliation intensity levels and compare predicted mortality to mortality of undefoliated trees to determine how gypsy moth defoliation will affect their stands. The probabilities can be used to develop marking guides based on projected defoliation levels for implementing silvicultural treatments to minimize gypsy moth effects in forest stands prior to infestation.

1 Introduction

Since the early 1980s, there has been growing interest on the part of forest land managers in the United States and Canada in using silvicultural treatments to manipulate the susceptibility and vulnerability of forest stands to gypsy moth *Lymantria dispar* L. infestation (Gottschalk 1982, 1987). Gypsy moth defoliation results in loss of growth, mortality, and shifts in species composition, among other effects in mixed-oak forests (Gottschalk 1990). Silvicultural guidelines have been developed that recommend treatments for reducing susceptibility to defoliation and vulnerability to mortality for stands treated prior to gypsy moth defoliation (Gottschalk 1993). To implement the silvicultural treatments for reducing vulnerability, guidelines are needed that can predict the probability of individual tree mortality following defoliation. Trees can then be marked for cutting so that trees with higher probabilities of mortality are cut and trees with lower probabilities of mortality are retained. In this way, the overall stand mortality is reduced to a manageable level. Herrick (1982) produced some individual tree mortality probabilities for north-eastern Pennsylvania, USA, based on tree crown condition, species and aspect. These probabilities were used for development of early marking guides (Gottschalk 1982).

However, there was need for better guides that were applicable to a larger area, so Herrick and Gansner (1987) analysed a large data set collected over a 7-year period in central Pennsylvania during the initial gypsy moth outbreak following invasion of the area. They used Automatic Interaction Detection (AID) analysis to produce a decision tree with 10 significantly different groups. Three variables were significant in their analysis:

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- Species group: black oak, *Quercus velutina* Lam. and chestnut oak, *Q. prinus*, other *Quercus* species, other species;
- Crown condition (vigour) before defoliation: good, fair, poor;
- Crown class (position): dominant and codominant, intermediate, suppressed.

These results, along with earlier work by HERRICK (1982), were used for subsequent marking guides (GOTTSCHALK 1993; GOTTSCHALK and MACFARLANE 1993). The advantages of their analysis are that it: provided a valid independent statistical test of important factors, provided structure to a large data set, determined regional risk of mortality across defoliation patterns, and identified characteristics to select trees for removal in silvicultural treatments (decision tree). The disadvantages of their analysis are: it does not use defoliation as a factor, although previous research shows it is a major factor; it underestimates mortality risk from defoliation because undefoliated trees are included; it cannot be used as a prediction tool for managers to compare defoliated vs. undefoliated scenarios; it raises doubts about using these risk factors to select trees for removal in silvicultural treatments. Because of these disadvantages, we decided to reanalyse HERRICK and GANSNER's data using defoliation as a factor in the analysis.

2 Materials and methods

2.1 Study variables

HERRICK and GANSNER (1987) analysed mortality risk of 14 684 trees located on 603 0.04 ha plots located in central Pennsylvania. The plots were established in 1978 and measured annually through 1985, with gypsy moth defoliation occurring between 1980 and 1982; most defoliation occurred in 1981. All trees were rated individually for defoliation in 10% classes. Half of the plots never had defoliation ≥30%. Mortality was assessed in 1985. They used 43 variables that included characteristics such as stand size, stand composition, tree diameter, species, stand age, crown position, crown condition, site index, land capability class, elevation, aspect, slope and position on slope. Some of the variables were plot based. Others were unique to the individual tree. HERRICK and GANSNER included the defoliation rating of each individual year as a variable, but none of these were a significant variable in their analysis.

We conducted a reanalysis of HERRICK and GANSNER's data using defoliation patterns. To get around the problems they had with data from separate years, we reclassified all of the defoliation data for all of the years into one variable with three classes. The classes used were:

- Undefoliated trees: ≤ 30% defoliation for every year (8051 trees);
- Moderately defoliated trees: >30% and ≤60% defoliation for one or more years (3040 trees);
- Heavily defoliated trees: >60% defoliation for 1 or more years (3593 trees).

Species were handled several different ways in the analyses. For the categorical analysis of variance, the three species groups used by HERRICK and GANSNER (1987) were used. There were 39 species present in the data set. However, a number of them were represented by only a few trees. To make the classification and regression tree (CART) analysis simpler, a second grouping of 14 species with fewer than 15 trees each were combined into a miscellaneous species group with the remaining 25 species kept separate. For the CART analysis using separate moderately and heavily defoliated classes, a third grouping of species included two groups of miscellaneous species: one for species that are preferred food (susceptible) of gypsy moth and one for species that are resistant or immune to gypsy moth feeding. These two groups included all species with fewer than 35 trees in them. The remaining nine or 10 species were kept separate.

2.2 Types of analyses

Categorical analysis of variance (SAS procedure CATMOD) using Herrick and Gansner's variables and species groups plus defoliation class was done to determine the significance of the variables and their interactions (SAS Institute 1989). The analysis was carried out by testing both a weighted least-squares ANOVA of the mortality probabilities and a log-odds-ratio (LOR) ANOVA. The initial model was full rank, considering the main effects, two-way, and three-way interactions of defoliation, species groups, crown position, and crown condition. The three-way interaction of defoliation, species groups, and crown condition was not significant, so it was dropped from the model. In addition, we controlled the two-way interactions of these variables by crown position and the significant three-way interactions were characterized by controlled two-way interactions. We arrived at similar final models using both analyses. Because the LOR ANOVA provided a better fit to the data, it is presented here. All indications of differences in survival or mortality in discussion of these results are judged through log-odds ratios.

CART, classification and regression trees, analysis, which is a decision tree analysis similar to AID, was used to develop mortality probability models (Breiman et al. 1984; Steinberg and Colla 1992). It is a tree-structured nonparametric data analysis package that uses a decision tree to classify or predict via a series of yes/no questions about variables and their values. The analysis can use both categorical and continuous variables and uses binary recursive partitioning to repetitively split variables into two pieces. The CART analysis includes both tree-pruning and a cross-validation routine that systematically removes 10% of the observations from the data set at a time and uses them to validate the analysis. The cross-validation results are presented as the percentage of live and dead trees that are correctly classified by the prediction model. CART models were run using all individual tree and plot variables, subsets of variables and separately for the three defoliation classes.

3 Results

3.1 Defoliation effects

The addition of defoliation class to the analysis done by Herrick and Gansner (1987) provided additional insight into the mortality patterns. Reduced mortality was found in undefoliated (14.5%) and moderately defoliated (17.9%) trees while heavily defoliated (28.4%) trees had increased mortality compared with the average (18.6%). The interactions of crown condition (vigour), crown position, and species group were used to further highlight the defoliation effects. Heavy defoliation caused an increase in mortality for trees of good or fair crown conditions, but had no effect on mortality of poor-crown trees (Fig. 1). Mortality was high in poor-crown trees irrespective of defoliation. Heavy defoliation increased mortality in all crown positions but was less influential in suppressed trees, where mortality was consistently higher (Fig. 2). Moderate defoliation caused higher mortality rates in both intermediate and suppressed trees relative to pooled values, but not in dominant/codominant trees. Heavy defoliation increased mortality for all species groups (Fig. 3). Undefoliated and moderately defoliated chestnut and black oaks had patterns that did not match the expected results and the other two species groups. Splitting Herrick and Gansner's 10 AID groups into defoliation classes resulted in increased mortality within an AID group as defoliation increased (data not shown).

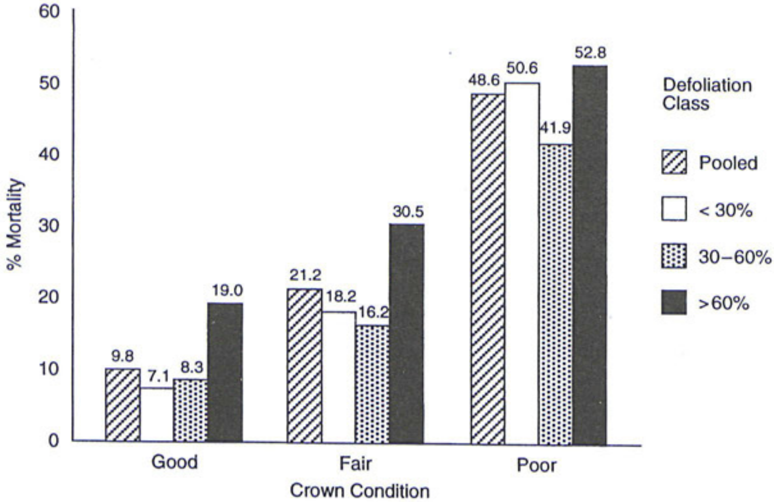


Fig. 1. Per cent mortality of all trees (pooled) and of trees in the three defoliation classes (undefoliated = ⩽30% defoliation, moderately defoliated = >30 and ⩽60% defoliation, heavily defoliated = >60% defoliation) in a two-way interaction with three crown condition classes

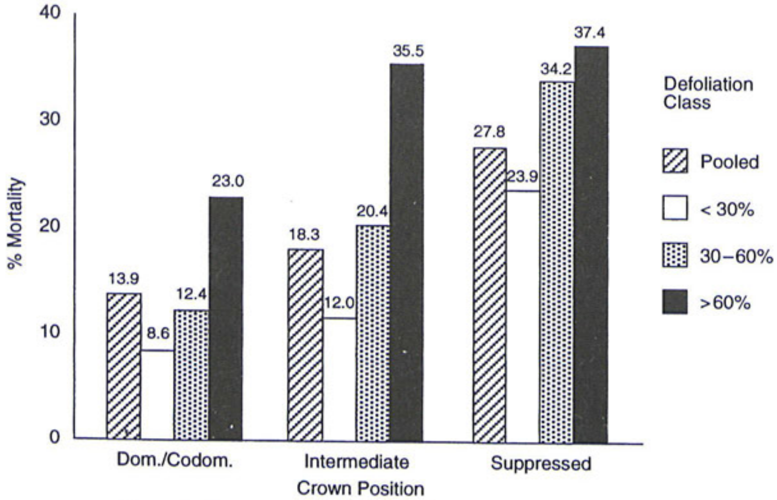


Fig. 2. Per cent mortality of all trees (pooled) and of trees in the three defoliation classes (undefoliated = ⩽30% defoliation, moderately defoliated = >30 and ⩽60% defoliation, heavily defoliated = >60% defoliation) in a two-way interaction with three crown position classes

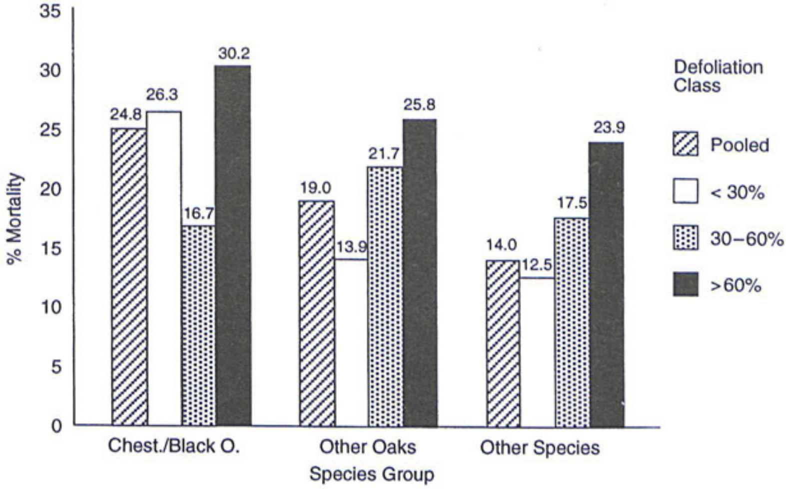


Fig. 3. Per cent mortality of all trees (pooled) and of trees in the three defoliation classes (undefoliated = ⩽30% defoliation, moderately defoliated = >30 and ⩽60% defoliation, heavily defoliated = >60% defoliation) in a two-way interaction with three species groups (chest./black O. = chestnut and black oaks, other oaks = all other oak species, other species = all species other than oak)

3.2 ANOVA

Species group, defoliation class, crown position, and crown condition were used to classify the proportion of trees that were dead for categorical analysis of variance (Table 1). In the following, all indications of differences in survival or mortality are judged through log-odds ratios.

The main effects all showed highly significant abilities to separate mortality effects in the

Table 1. **Maximum-likelihood analysis-of-variance table (log-odds ratio) for individual tree mortality, as influenced by defoliation class (D), crown position class (CP), crown condition or vigour class (CV), and species group (Sp)**

Source	DF	χ^2	Probability
Intercept	1	829.31	0.0000
Defoliation	2	93.22	0.0000
Species	2	49.46	0.0000
Crown position	2	133.10	0.0000
Crown vigour	2	556.04	0.0000
D*CP	4	49.42	0.0000
Sp*CP	4	50.03	0.0000
CP*CV	4	11.70	0.0197
D*Sp(CP = 1)	4	29.37	0.0000
D*Sp(CP = 2)	4	27.86	0.0000
D*CV(CP = 1)	4	12.68	0.0129
D*CV(CP = 3)	4	21.19	0.0003
Sp*CV(CP = 1)	4	9.28	0.0545
Sp*CV(CP = 2)	4	15.48	0.0038
Liklihood ratio	36	45.33	0.1370

expected order. As can be seen from the χ^2 test results (Table 1), tree vigour had the strongest effect on survival, suggesting that vigour rating a forest stand will better than triple one's ability to predict tree mortality. While the species grouping did the least to separate tree mortality as an independent predictive agent, it performed strongly when combined with crown position.

The interaction of defoliation with crown position indicates that survival decreases as one moves from the upper canopy downward, looking only at the undefoliated trees. This trend reverses and mortality increases as one examines the trees with heaviest defoliation; no trend exists for those trees where defoliation was moderate. For species groups and crown position, survival increased from lower to upper canopy for black and chestnut oaks and other oaks while among other species, this trend is reversed. Finally, the interaction of crown condition with crown position in the canopy is the weakest and does not exhibit consistent trends, except that the main effect of crown condition is reversed among the suppressed trees, i.e. survival trend increases among the suppressed trees as the crown condition goes from good to fair to poor.

The three-way interactions were examined by considering them as controlled two-way interactions; only six of the nine were significant. Their interactions were quite weak and only defoliation interactions with species groups were consistent enough to observe trends. Among the dominant/codominant and intermediate crown classes, black and chestnut oaks that were undefoliated had higher mortality, while those black and chestnut oaks that were moderately defoliated tended to survive better. In the dominant/codominant class, other oaks that were moderately defoliated showed increased mortality while others that were heavily defoliated showed increased survival; other species that were heavily defoliated showed higher mortality. In the intermediate crown class, non-oak tree species showed better than average survival when undefoliated and higher mortality from moderate defoliation; heavily defoliated black and chestnut oaks survived better. Defoliation interaction with crown condition showed some significant variation in the upper canopy and among the suppressed trees while no significant variation was seen among the intermediate trees. In both the top (dominant/codominant) and bottom (suppressed) of the canopy, high vigour trees that were undefoliated showed high survival and heavily defoliated ones showed high mortality. In these two crown positions, heavily defoliated low-vigour trees showed higher than expected survival. The interaction of species groups with crown condition in the upper- and mid-canopy strata showed that non-oak species of high vigour had higher survival rates while black and chestnut oaks of high vigour in the upper canopy showed increased mortality across the defoliation classes.

3.3 CART

The best decision tree developed with all individual tree and plot variables, 25 species and one species group, and defoliation classes available for inclusion, had 65 groups for defining mortality risk. The most important variables were species and crown condition. Mortality risks of the 65 groups varied from 0 to 69%. Variables included were: species, crown condition, crown position, age, d.b.h., elevation, defoliation class, aspect, slope position, slope percentage, and site index. Cross-validation test results showed 75.4% of live trees were classified as live and 76.5% of dead trees were classified as dead. This model is good predicting mortality probabilities but it has some disadvantages. It is so large and complex with so many different combinations that it is too complicated for field use; also, since most marking for mortality is generally done within a stand, the plot variables are of limited use because these are usually the same within a stand. Defoliation classes were scattered throughout the decision tree and were very difficult to use in a predictive way for comparing different defoliation scenarios.

To overcome these disadvantages, a reduced model for relative prediction within a stand was developed that dropped defoliation classes and plot variables since these do not vary within a stand. The best reduced decision tree had 20 groups for defining mortality risk. The most important variables were species and crown condition. Mortality risks of the 20 groups varied from 3 to 52% (Fig. 4). Variables included were: crown condition, species, crown position, and d.b.h. Cross-validation test results showed that 72.0% of live trees were classified as live and that 72.2% of dead trees were classified as dead. This model would be similar to the 10 AID groups that HERRICK and GANSNER (1987) developed, except that it has 10 more significantly different groups than theirs. The reduced model has not lost very much in terms of accuracy, but with 20 groups, it is still too complicated for field use. The reduced model also does not allow managers to estimate mortality under different defoliation scenarios, since defoliation classes were dropped.

To take defoliation back into consideration while still maintaining simplicity, the data set was split into three data sets with the defoliation classes serving as the basis for splitting; this resulted in data sets for heavily defoliated trees, moderately defoliated trees, and undefoliated trees. Species groups were reordered into a preferred group, an immune group, and nine or 10 separate species. For heavily defoliated trees, the best decision tree had seven groups for defining mortality risk (Fig. 5). The most important variables were species and crown condition. Mortality risks of the seven groups varied from 16 to 88% (Fig. 5). Variables included were: crown condition, species, crown position, and d.b.h. Cross-validation test results showed that 62.8% of live trees were classified as live and that 69.2% of dead trees were classified as dead.

For moderately defoliated trees, the best decision tree had five groups for defining risk of mortality. The most important variable was crown condition. Mortality risks of the five groups varied from 7 to 42% (Fig. 6). Variables included were: crown condition, species, and crown position. Cross-validation test results showed that 71.7% of live trees were classified as live and that 68.5% of dead trees were classified as dead.

For undefoliated trees, the best decision tree had 10 groups for defining mortality risk.

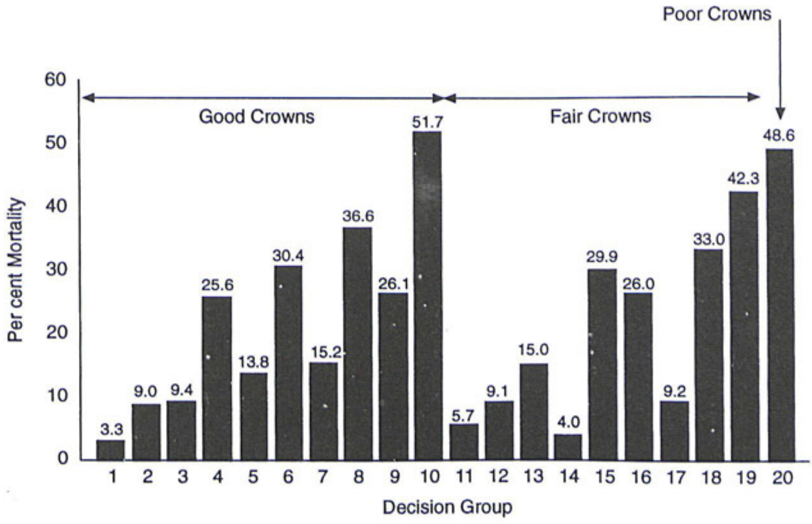


Fig. 4. Per cent mortality of trees that have been classified into 20 significantly different decision groups using CART analysis of individual tree variables without plot variables or defoliation

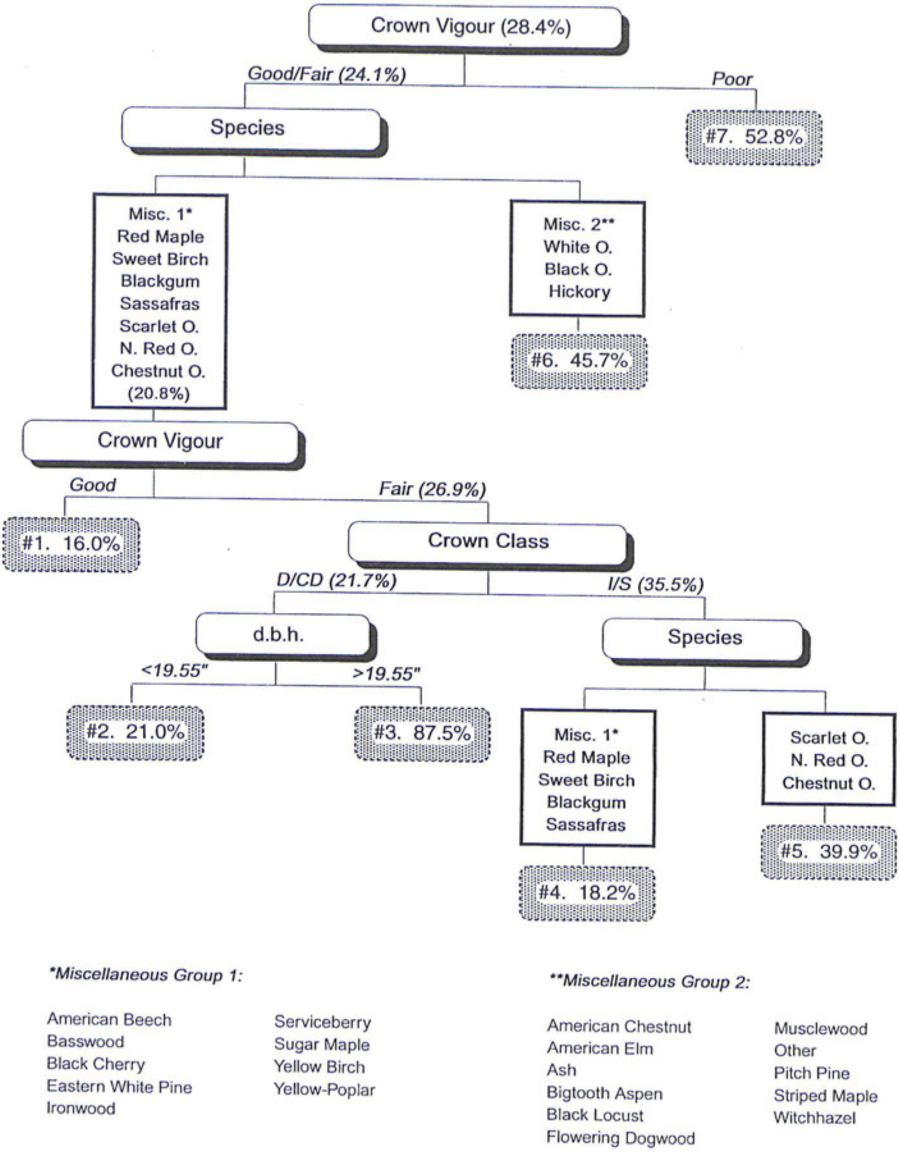
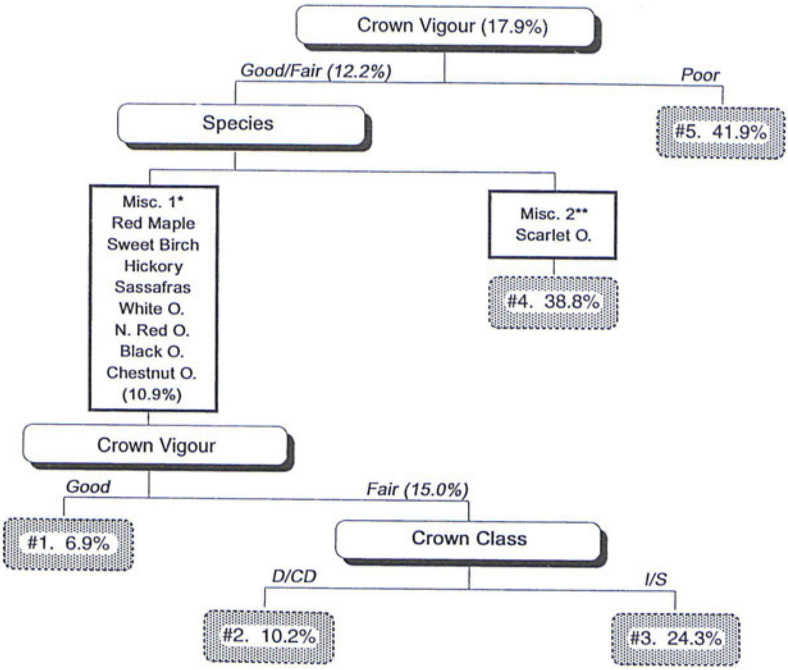


Fig. 5. CART analysis decision tree structure using the heavily defoliated tree data, including individual tree variables without plot variables

The most important variables were species and crown condition. Mortality risks of the 10 groups varied from 2 to 53% (Fig. 7). Variables included were: species, crown condition, crown position, and d.b.h. Cross-validation test results showed that 75.6% of live trees were classified as live and that 78.5% of dead trees were classified as dead.



Miscellaneous Group 1:

Ash
Basswood
Black Cherry
Blackgum
Eastern White Pine
Pitch Pine
Sugar Maple

****Miscellaneous Group 2:***

American Beech
American Elm
Bigtooth Aspen
Black Locust
Butternut
Flowering Dogwood
Musclewood
Quaking Aspen
Slippery Elm
Striped Maple
Witchhazel
Yellow Birch
Yellow-Poplar

Fig. 6. CART analysis decision tree structure using the moderately defoliated tree data, including individual tree variables without plot variables

4 Discussion

4.1 Defoliation Effects

Defoliation is a significant variable in predicting mortality risk which was not supported by earlier analysis of this same data set by HERRICK and GANSNER (1987). The reasons for the differences between their results and ours lie in the way that defoliation was used in the analysis. The previous work used raw individual tree defoliation ratings for each year as separate variables. Data for any given year on its own was not very highly correlated with the mortality that occurred. Our approach of classifying trees based on the highest amount of defoliation they received in any year into one of three classes, resulted in a classification that more closely represents other reported influences of defoliation (CAMPBELL and SLOAN 1977). While not examined in this paper, it may be possible to refine further this analysis

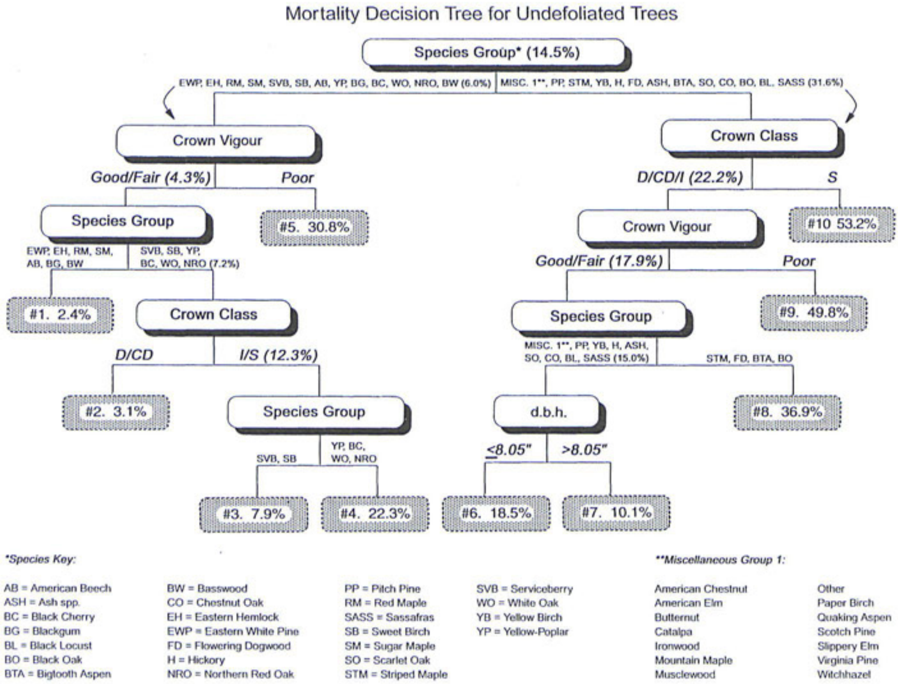


Fig. 7. CART analysis decision tree structure using the undefoliated trees data, including individual tree variables without plot variables

approach by creating additional classes that take the frequency of defoliations within a defoliation intensity class into account (i.e. 1 vs. 2 vs. 3 years).

4.2 ANOVA analysis

Tree mortality is notoriously difficult to model because it can be caused by many different factors and is generally a random process over time. Significant results for all four variable main effects, the intercept, and several of the interactions produce a tool for modelling the mortality of trees following gypsy moth mortality. Crown condition (vigour) was the most important variable in the analysis for predicting mortality. This result supports previous work in gypsy moth – forest interactions (CAMPBELL and SLOAN 1977). While mortality is only correlated with these factors and not necessarily caused by them, some problems in prediction are bound to occur in the use of these relationships. Owing to the large, complex nature of the log-odds-ratio ANOVA model and the significant interactions present, it is hard to understand the relationships and to use them in a predictive way. For this reason, we pursued the CART analysis approach.

The significant interactions of defoliation class with the other variables suggests that, in some cases, such as poor-crown trees or suppressed trees, defoliation made little or no difference in mortality rates. Conversely, heavy defoliation on intermediate crown trees caused the largest increase in mortality. Mortality is difficult to explain for undefoliated chestnut and black oaks, which had a higher than expected mortality rate compared with other defoliation patterns. Factors other than defoliation such as drought stress, site conditions, stand conditions, or age may have resulted in the high mortality of these trees. The relationships of the interactions were sometimes counterintuitive to the expected result based on the main effects.

4.3 CART analysis

The CART analysis technique is very useful for developing graphical decision trees that can be used to predict tree mortality given the values of the variables used in the decision tree. CART decision trees can be very complex, as demonstrated by the best decision tree which had 65 groups. However, it correctly classified the highest percentages of live and dead trees. If these decision tree models are incorporated into computer programs or decision support systems, this complexity is not a disadvantage, but they are too complicated for foresters in the field.

Dropping plot variables and dividing the data into three groups by defoliation class resulted in three smaller, simpler decision trees that can be easily used in the field by foresters. Their use should be restricted to relative comparisons of defoliation levels within a stand or stand comparisons within a defoliation level. The heavily defoliated trees had seven groups in the decision tree and correctly classified to within 12% of the live trees and 7% of the dead trees compared with the large complex model. The best decision tree for moderately defoliated trees had five groups and correctly classified to within 3% of the live trees and 7% of the dead trees compared with the large complex model. Using these decision trees for moderately or heavily defoliated trees to compare different defoliation scenarios with undefoliated tree mortality risks reduces the underestimation of risk and provides valuable estimates of the potential effects of gypsy moth defoliation on mortality of forest stands. The best decision tree for undefoliated trees had 10 groups and correctly classified at the same or slightly better rates than the larger complex model.

Crown condition and species were the most important variables in all of the decision trees and crown position was often present. This result agrees with and supports the ANOVA results. In addition, d.b.h. entered into many of the CART analyses, showing how variables that are not significant in the entire data set can be significant when analysed on a subset of the data where they can have great influence. This flexibility is one of the strengths of the nonparametric approach which makes no assumptions about the structure of the data.

Individual tree marking guides for removing trees within a stand have been based on previous work that developed individual tree mortality probabilities. Thus, the validity of the mortality models is closely tied to the validity of the marking guides. Moreover, the success of the silvicultural treatments is, in turn, tied closely to the validity of the marking guides. This paper supports the observation that crown condition, species, crown position and d.b.h., respectively, are the most important variables for selecting trees to remove. All of these variables are easy to use marking guides in the field. In addition, marking guides can now be adjusted based on the level of defoliation that is expected in the stand. A relatively pure oak stand would be expected to have heavy defoliation while a mixed oak – hardwood stand would have moderate defoliation. Separate marking guides can be used with both of these situations.

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Résumé

Risques de mortalité chez le chêne par Lymantria dispar

Des modèles prédictifs sont présentés pour estimer la mortalité d'arbres à la suite de la défoliation par *Lymantria dispar* dans des chênaies mélangées. Ces modèles diffèrent des précédents car ils utilisent la défoliation comme un des facteurs de l'analyse. Dans l'analyse de variance par catégories, l'intensité de la défoliation, l'état initial du houppier (vigueur du houppier), la position du houppier et les classes de groupes d'espèces étaient très significatifs pour la mortalité. Une défoliation sévère avait une influence forte et constante sur l'augmentation de la probabilité de mortalité. L'analyse CART (Classification and Regression Tree), une procédure binomiale de décision en arborescence, a été utilisée pour développer des modèles de prédiction du risque de mortalité à l'usage des gestionnaires. La meilleure arborescence de décision avait 65 groupes; elle classait correctement 75% des arbres vivants et 76% des arbres morts. Les modèles ont été appliqués séparément aux classes de défoliation et ont fourni des classements corrects pour 63 à 78% des arbres. Les gestionnaires peuvent utiliser ces modèles pour assigner des probabilités de mortalité à des niveaux de défoliation modérés et forts et pour comparer les mortalités prévues aux mortalités des arbres non défoliés, afin de déterminer dans quelle mesure le *Lymantria dispar* affectera leurs peuplements. Les probabilités peuvent être utilisées pour établir des guides de martelage basés sur des niveaux prévus de défoliation pour effectuer, avant l'infestation, les traitements sylvicoles qui minimisent les effets du *Lymantria dispar*.

Zusammenfassung

Mortalitätsrisiko von Eichen nach Befall mit Lymantria dispar

Es werden Prognosemodelle zur Abschätzung der Baumvitalität nach Befall durch den Schwammspinner (*Lymantria dispar*) in Eichenmischwäldern (*Quercus* spp.) präsentiert. Diese Modelle unterscheiden sich von früheren Ansätzen dadurch, dass in den Analysen der Blattverlust berücksichtigt wird. In der kategorialen Varianzanalyse für die Mortalität zeigten die folgenden Parameter einen hochsignifikanten Einfluss: Intensität des Blattverlustes, Kronenzustand vor dem Befall (Kronenvitalität), soziale Stellung und Artenzusammensetzung des Bestandes. Schwere Blattverluste waren stark und gleichmässig mit der zunehmenden Wahrscheinlichkeit des Absterbens korreliert. Zur Entwicklung von praxistauglichen Prognosemodellen für die Baummortalität wurde die CART-Analyse, ein binomiales Entscheidungsverfahren, verwendet. Das beste Modell umfasste 65 Risikogruppen und klassifizierte 75% der lebenden und 76% der abgestorbenen Bäume korrekt. Die Modelle wurden separat auf die verschiedenen Blattverlustklassen angewendet und lieferten für 63–78% der Bäume korrekte Klassifikationen. Diese Modelle können in der Praxis zur Vorhersage des Mortalitätsrisikos nach mittleren und schweren Blattverlusten eingesetzt werden. Ausserdem kann damit die prognostizierte Mortalität mit der Mortalität von nicht befallenen Bäumen verglichen, und so die Auswirkung eines *L. dispar* – Befalles auf die Bestände bestimmt werden. Aufgrund der Mortalitätswahrscheinlichkeiten in Abhängigkeit vom Blattverlust können bereits vor einem Befall Richtlinien für die waldbauliche Behandlung entwickelt werden, um die Auswirkungen einer *L. dispar* – Kalamität zu minimieren.

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