SPECIAL REPORT

Michigan Agricultural Experiment Station, Michigan State University

Status and Potential of Michigan Natural Resources

SAPMINR

Economic Consequences of Jack Pine Budworm Outbreak

Final Report

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Reports on the Status and Potential of Michigan Natural Resources

This special research report is one of a series (listed on p. 3) prepared for a project of the Michigan Agricultural Experiment Station (MAES) called the Status and Potential of Michigan Natural Resources (SAPMINR).

The project, funded jointly by MAES and the Office of the Provost, was designed to inventory the current status of Michigan natural resources, identify emerging trends and appraise future opportunities. The purpose was to assist the MAES in establishing research priorities and planning programs.

Both overview and focused topic assessments have been made. The overview reports provide background information on the political, economic and social environments influencing Michigan natural resources. The focus reports examine specific resources, including timberland, fisheries and wildlife, parks and recreational, and land and water resources.

The SAPMINR project began in early 1993. At that time, interdisciplinary teams of MSU faculty members, graduate students, federal and state government officials, and others collaborated to develop preliminary reports. In March 1994, a SAPMINR conference during MSU's Agriculture and Natural Resources Week provided a public forum for discussion of the preliminary reports. Based on interaction with conference participants, the authors prepared the final drafts of the overview and focus reports listed below.

SAPMINR Reports

Overview Reports

SR 67 – SAPMINR Highlights

SR 68 – Michigan Natural Resources Policy

SR 69 – Demographic, Social and Economic Trends

SR 70 – Integrated Natural Resource Systems

Focus Reports

SR 71 – Timber and Timberland Resources

SR 72 – Lumber, Furniture, Composition Panels and Other Solidwood Products

SR 73 – Pulp, Paper, Allied Products and Wood Energy

SR 74 – Fisheries

SR 75 – Wildlife

SR 76 – Tourism

SR 77 – Boating and Underwater Recreation

SR 78 – Camping, Trails and Dispersed Recreation

SR 79 – Water Resources

SR 80 – Land Resources

SR 81 – Non-renewable Resources

SR 82 – Natural Resources and Communities

Once the trends and future opportunities were agreed upon, the MAES issued a call for research proposals to address issues and problems related to the highest priorities of Michigan's natural resources. Of the 38 pre-proposals received, the MAES selected 15 to be developed into full proposals. Ultimately, 10 were selected and funded at a total of almost $1.2 million over three years. The research findings of those SAPMINR projects were published as a series of Michigan Agricultural Experiment Station special reports (listed on p. 3)

To receive any of these SAPMINR research reports, contact the MSU Agricultural Experiment Station, 109 Agriculture Hall, Michigan State University, East Lansing, MI 48824-1039.

SAPMINR Research Reports

SR 103 Perceptions, Preferences and Behaviors of Selected Outdoor Recreationists Concerning Michigan State Forest Campgrounds and Pathways

RR 568 The Role of Natural Resources in Community and Regional Economic Stability in the Eastern Upper Peninsula

SR 104 Spatial Distribution and Economic Impacts of Recreational Boating in Michigan

SR 105 Economic Consequences of Jack Pine Budworm Outbreaks

SR 106 Development of Methods and Guidelines for Local Wetland Protection and Related Land Use Planning

SR 107 Response of Fish and Wildlife Macrohabitat to Changes in Land Use and Land Cover

SR 108 Regional Michigan Travel Marketing Survey

SR 109 Foundations of Ecosystem Management: Integrating Sociological and Ecological Components

SR 110 Natural Resources and Tourism in Michigan: Potential Products, Satisfactions and Barriers

SR 111 Michigan's Mineral Wealth

SR 112 Waste: A Hidden Resource

SR 113 Hunting, Fishing and Wildlife-watching Expenditures in Michigan

SR 114 Michigan's Forest Products Industry

SR 115 Agricultural Production in Michigan

SR 116 Michigan's Tourist Industry

SR 117 Michigan's Natural Resources Endowment: A Summary

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Economic Consequences of Jack Pine Budworm Outbreaks

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Table of Contents

Executive Summary

Jack pine (*Pinus banksiana*) ecosystems are economically and ecologically significant in the Great Lakes region of the United States and throughout much of Canada. Jack pine is a fast-growing species that is well adapted to excessively dry, sandy soils where other trees cannot survive. In Michigan, jack pine grows on nearly 850,000 acres and represents roughly half of the total pine acreage in the state. More than 250,000 cords of jack pine are harvested annually for fiber production in Michigan (Piva, 1997), and the use of jack pine for dimension lumber is steadily increasing. In addition to providing a substantial resource for the forest products industry, jack pine ecosystems also contribute to wildlife habitat and recreational opportunities for Michigan residents. Jack pine forests in Michigan provide habitat for the endangered Kirtland's warbler (*Dendroica kirtlandii*), and the endangered Karner Blue butterfly (*Lycaedis melissa samuelis*) occupies jack pine barrens in Wisconsin. Deer, grouse and non-game species such as sandhill cranes frequently live in jack pine forests in Michigan (Heym et al., 1993). Interest in managing jack pine stands has grown in recent years because of dramatic increases in the value of jack pine for pulp (from $4/cord in 1991 to $30/cord or more in recent years), an abundance of overmature jack pine stands and more emphasis on utilizing some jack pine stands for non-timber objectives.

Jack pine budworm (*Choristoneura pinus pinus* Freeman) is a native defoliator and the most important pest affecting jack pine (Howse, 1984). Outbreaks of jack pine budworm (JPBW) occur at six- to 10-year intervals, and each outbreak may persist for two to four years before populations collapse (Volney and McCullough, 1994). Defoliation by the budworm larvae can reduce rates of tree growth, kill the upper crowns of trees (topkill), kill entire trees and increase the risk of wildfire (Kulman et al., 1963; Gross, 1992; McCullough et al., 1996). During a JPBW outbreak, defoliation is typically widespread, but the amount of damage — i.e., tree mortality and topkill — differs substantially among stands (Kouki et al., 1997; McCullough et al., 1996). Mortality generally continues for a few years after defoliation ends because of reduced tree vigor and low resistance to environmental stress or secondary pests. Over time, stands accumulate dead trees and topkilled trees, increasing the potential for intense wildfires.

Information about the impact of cyclic defoliators such as JPBW is needed to quantify the loss of timber volume resulting from an outbreak and to identify the site or stand characteristics that are associated with heavy damage during a JPBW outbreak. This knowledge will enable managers to prioritize vulnerable stands for harvest, pest surveys or other action. For example, stands that are likely to be heavily damaged during a JPBW outbreak could be scheduled for harvest before less vulnerable stands. Alternatively, highly vulnerable stands may be more appropriately managed for wildlife habitat or converted to a different species. Accurate estimates of tree mortality and volume loss are also needed by managers involved in the forest planning process to ensure that harvests do not exceed sustainable levels.

In 1996, we intensively surveyed 99 stands (3,600 acres) to quantitatively assess the biological and economic impact of a JPBW outbreak that occurred during 1991-1993 in the Raco Plains region of the Hiawatha National Forest in the eastern Upper Peninsula of Michigan. Hiawatha National Forest personnel provided updated inventory and spatial data. We used growth-and-yield models and economic modeling to determine losses in standing and projected merchantable volume and financial value resulting from the 1991-1993 JPBW outbreak. Site and stand characteristics associated with relatively high rates of damage and value loss were identified.

We found that an average of 16 percent of all jack pine trees eventually died and 18 percent sustained topkill as a result of the 1991-1993 JPBW outbreak. Growth of trees that survived the outbreak was reduced by 28 percent annually from 1992 to 1994. On average, the standing volume loss was 2.3 cords/acre and standing value loss was $78/acre. Standing volume and value losses totaled 8,200 cords and $289,800, respectively, for the 3,600-acre area that was sampled.

Stands that were 50 years old or older sustained higher losses than younger stands, a result that was anticipated. However, we also found that stands growing on relatively good sites (site index > 50) sustained significantly more mortality than stands on poorer sites (site index ≤ 50), regardless of stocking level. This result was unexpected but was consistent among years. It indicates that silvicultural guidelines should be modified to prioritize harvest of old stands on high quality sites. Although volume loss was correlated with basal area, there were no significant differences in value loss among understocked (0 to 70 ft^2/ac), well stocked (71 to 110 ft^2/ac) or overstocked (> 111 ft^2/ac) stands. This indicates that in well stocked and overstocked stands, much of the mortality was concentrated on small or suppressed trees. Thinning, therefore, is unlikely to be an economically viable management option in overstocked stands. Results from our surveys and analyses were used to develop the Lake States Jack Pine Budworm Decision Support System (DSS) to assist resource managers with forest planning and silvicultural decisions. After testing and development of a user's guide, the DSS was delivered to the Hiawatha National Forest and is currently being used by forest personnel to manage the jack pine resource.

Environmental and Economic Benefits to Michigan

Jack pine forests cover nearly 850,000 acres in Michigan, about half of the total pine acreage in the state. This boreal forest species plays an important ecological role in the state. It grows rapidly and tolerates relatively poor, sandy soils where other forest species cannot live. In Michigan, jack pine forests provide habitat for at least 42 bird species, including the endangered Kirtland's warbler, and many other game and non-game wildlife species. Michigan residents use jack pine forests for year-round recreational activities such as snowmobiling, cross-country skiing, birdwatching, berry picking and hunting.

Jack pine is an economically important component of Michigan's forest products economy. This industry employed about 109,000 people in 1992 with $3.2 billion in value-added. More than 250,000 cords of jack pine are harvested annually for fiber production in Michigan, amounting to a stumpage value of $7.5 million, and the use of jack pine for dimension lumber is steadily increasing. Income generated by tourism-related activities in jack pine forests is an important part of local economies in much of northern lower Michigan and the Upper Peninsula.

Jack pine budworm is the most important pest affecting jack pine. Outbreaks of this defoliating insect occur every six to 10 years and can result in tree mortality, topkilled trees and substantial growth loss. Wildfire risk typically increases after an outbreak because of an accumulation of dead and topkilled trees. Chemical pesticides are not used to control jack pine budworm in the United States for environmental and economic reasons.

Forest managers require information about the impact of a jack pine budworm outbreak and the types of stands most likely to be damaged during an outbreak. This information will help ensure that forests are managed on a sustainable basis and help foresters prioritize stands for harvest or other management activities.

In this multidisciplinary project, we quantified the amount of growth loss, topkill and tree mortality that resulted from a 1991-1993 jack pine budworm outbreak in the eastern Upper Peninsula. On our 3,600-acre study area, the economic loss associated with this outbreak was $289,800. We were also able to identify the key site or stand traits associated with stands that sustained relatively heavy damage and those that sustained negligible damage. These results were used to develop silvicultural recommendations that will help forest managers substantially reduce the damage from future budworm outbreaks.

In addition, we were able to transfer the results of our project directly to forest managers. We incorporated the knowledge generated by this project into the Lake States Jack Pine Budworm Decision Support System. This system integrates growth-and-yield models, economic models and jack pine budworm impacts to assist resource managers with forest planning and silvicultural decisions. The system quantifies tree growth, timber volume and timber value over time, then calculates the loss expected to result from future budworm outbreaks. Users can identify and map vulnerable stands using a geographic information system (GIS), and numerous tables and charts are produced to help managers with the forest planning process. The USDA Forest Service is currently using our decision support system for jack pine management in northern lower Michigan and the Upper Peninsula. Personnel from the Michigan Department of Natural Resources have also expressed interest in utilizing the system after they update their GIS capabilities.

Problem Statement

Jack pine is an economically and ecologically important species in Michigan, other states in the Lake States region and much of Canada. It grows rapidly, tolerates dry, sandy soil, and is heavily utilized for softwood pulp and increasingly for dimension lumber (Rudolph and Laidly, 1990). Recent estimates suggest that jack pine accounts for 38 percent of the softwood pulp production in the Lake States (Piva, 1997). In Michigan, jack pine grows on nearly 850,000 acres and often occupies marginally productive land that other species do not tolerate. It provides habitat for the endangered Kirtland's warbler and other wildlife, and recreational opportunities for Michigan residents.

Jack pine budworm (JPBW) is a native defoliator that is found throughout most of the jack pine range. Outbreaks occur at six- to 10-year intervals, and defoliation persists for two to four years before populations collapse (Volney and McCullough, 1994). During an outbreak, heavy defoliation is often concentrated in the tops of trees, leading to death of the terminal leader and up to several feet of the upper canopy (topkill). Severe defoliation can kill trees, and tree mortality may continue to accumulate for two to three years after defoliation ends. Growth rates of defoliated trees are reduced, and trees may become more susceptible to other pests or harsh environmental conditions. Over the course of a 50- to 60-year rotation, stands may experience five or more JPBW outbreaks. Accumulation of topkilled and dead trees may result in intense wildfires if ignition occurs during a dry season.

To date, only a few investigations have collected stand-level data on the biological impacts of a JPBW outbreak (Kulman et al., 1963; Gross, 1992; McCullough et al., 1996). Virtually no data link stand-level impacts with estimates of productivity or economic loss. Only one previous effort was made to analyze effects of JPBW outbreaks on economic returns from Michigan jack pine forests (Nyrop et al., 1983). Those investigators, however, used only general models of tree growth and rough estimates of growth loss resulting from defoliation, and they did not consider mortality or topkill in their evaluation.

Interest in jack pine management has grown in recent years because of dramatic jumps in the value of jack pine — from $4/cord in 1991 to $28 to $30/cord — that increased pressure to maximize benefits from forested land. In addition, an abundance of overaged jack pine stands exists throughout northern lower Michigan and the Upper Peninsula. In the United States, forest managers do not use insecticides to control JPBW defoliation because of economic and environmental considerations. Instead, managers rely on silvicultural guidelines that address rotation length, harvest scheduling, stocking density, and salvage or cover-type conversions to minimize the impact of a JPBW outbreak. However, these guidelines had never been quantitatively evaluated, and reductions in timber yield resulting from a JPBW outbreak had not been previously quantified. Our goals in this study were to quantify stand-level biological and economic losses resulting from a 1991-1993 JPBW outbreak in the Raco Plains area of the Hiawatha National Forest in the eastern Upper Peninsula, identify the site or stand characteristics associated with high levels of loss, and evaluate the current JPBW management recommendations used in Michigan and other states in the Great Lakes region. In addition, we were able to use our results to develop the Lake States Jack Pine Budworm Decision Support System and provide it to the Hiawatha National Forest personnel to assist with management of the jack pine resource.

Objectives

- Survey the biological impact of a 1991-1993 JPBW outbreak (mortality, topkill, growth loss) in 99 stands (3,600 acres) in the Raco Plains area of the Hiawatha National Forest.
- Quantify volume reduction and economic consequences of the 1991-1993 JPBW outbreak in the surveyed stands.
- Use inventory variables (tree age, size, basal area, etc.), soil survey and Ecological Classification and Inventory (EC&I) data to identify traits of stands sustaining high economic losses relative to other stands.
- Examine the association between economic loss and biological impact.
- Develop a decision support system for the JPBW in the Hiawatha National Forest.

Procedures

We intensively surveyed 99 jack pine stands in four management compartments (3,600 acres total) to quantify the biological impact (tree mortality, topkill and growth loss) of the 1991-1993 JPBW outbreak in the eastern Upper Peninsula. At least two fixed-radius, 1/40-acre circular plots were randomly located in each stand, with more plots allocated to larger stands. Within each plot, all trees were counted and the diameter, height and crown ratio of jack pine trees were recorded. If trees were topkilled, the length of the dead top and the tree diameter at the margin of the dead top were determined. Abundance of fine twigs, sloughing bark, decay and other characteristics were examined on topkilled and dead trees to determine if the damage occurred before or after the 1991-1993 outbreak. A total of 277 plots and more than 3,000 jack pine trees were measured in 1996. McCullough provided data from annual surveys of tree mortality and topkill in these same stands from 1992 to 1995 to evaluate accumulation of damage over time (McCullough et al., 1996). Mortality and topkill were related to site and inventory variables using analysis of variance, correlation, chi-square analysis and modeling.

To assess annual radial growth, stands were grouped into 12 strata on the basis of stand age, site index and basal area. One stand was randomly selected from each stratum. Within each stand, three undamaged, two topkilled and two dead trees were randomly located (total of 84 trees) in 1996. These trees were felled and cross-sections taken at stump height and breast height and at 2-meter intervals beyond. The disks were kiln-dried and sanded, and two radii were located across the face of each disk. Annual ring width was measured along the two radii with an optical digitizing scanner and WinDENDRO image analysis software (Regent Instruments, Inc., Quebec, Que.) (Guay et al., 1992). Growth during the outbreak and the recovery period were compared using mean annual growth rate during five previous non-outbreak years as a reference value. Growth reduction and recovery rates were compared among trees that died as a result of the 1991-1993 outbreak, trees that were topkilled and trees that survived with no apparent damage. Growth rates were related to site and inventory variables as indicated above. In addition, we obtained historical accounts of JPBW defoliation from the Michigan Department of Natural Resources and USDA Forest Service pest reports and sketch maps. Growth rates were plotted against time, enabling us to identify loss and recovery of radial growth associated with previous JPBW outbreaks.

Data from the 1996 field surveys were used to generate a tree list for a USDA Forest Service growth-and-yield model. The Lake States TWIGS (LS-TWIGS) variant of the Forest Vegetation Simulator was used to estimate merchantable volume for trees in 1996. Tree list adjustments were made and the model was rerun to compare merchantable volume in the absence of the JPBW outbreak and with the loss attributable to the outbreak (incorporating tree mortality and growth loss). The LS-TWIGS model was used to compute standing merchantable volume loss and projected volume loss, where the impacts of the 1991-1993 outbreak were projected for all trees less than 50 years old. Price data were acquired from the Forest Service jack pine timber sales on the Raco Plains area in 1996. The mean price for jack pine pulp was used to compute standing and projected value losses for stands less than 50 years old.

Standing volume and value loss were related to stand age, site index, basal area, stand size, abundance of wolf trees (open-grown, full-canopied trees) and abundance of suppressed trees in each stand. Standing value loss was plotted against stand area and other variables, and non-parametric correlation coefficients were determined. Jack pine management recommendations were evaluated by classifying all stands into two age classes (0 to 50 years and 50+ years old), two site index classes (poor = < 50 and good = >50) and three stocking classes (understocked = < 70 ft^2/ac, well stocked = 71-110 ft^2/ac and overstocked = 110+ ft^2/ac). Chi-square analyses and non-parametric correlation analysis were used to compare biological and economic losses in relation to the classes.

Results

Mortality and topkill: Tree mortality continued to accumulate for two to three years after the outbreak collapsed, then leveled off. Mortality increased exponentially from 1 percent in 1992 to 3 percent in 1993 to 8 percent in 1994 and 16 percent in 1995. Mortality then leveled out, and surveys in 1996 again showed that, overall, 16 percent of the jack pine trees died as a result of the 1991-1993 outbreak. Within individual stands, mortality ranged from 0 to over 40 percent. Topkill resulting from heavy defoliation in the upper canopy of trees affected an additional 17 to 19 percent of all trees and ranged from 0 to 90 percent of trees within individual stands. These values undoubtedly underestimate the true impact of the 1991-1993 outbreak. Our survey included young stands as well as merchantable stands, and young trees are much more likely than older trees to survive heavy defoliation. Furthermore, 15 highly vulnerable stands (336 acres) were salvaged while this study was in progress. If the damage in these stands had been included, the impact estimates likely would have been greater.

Growth: On average, tree growth was reduced by 24 to 38 percent annually during the period of 1991-1994. Total reduction in growth of surviving trees totaled 133 percent of pre-outbreak growth. Growth was reduced in most trees for two years during the outbreak and for one additional year after defoliation ceased. We were able to use reports of past JPBW outbreaks and document long-term cycles of growth and recovery in relation to outbreaks. These data suggest that topkill may increase the vulnerability of trees to mortality during subsequent outbreaks (Conway et al., 1999a).

Volume and value loss: We used the tree mortality, topkill and growth loss data collected during the 1996 field season to quantify the reduction in merchantable volume and economic loss associated with the 1991-1993 JPBW outbreak (Conway et al., 1999b). Our estimates indicated that a total of 8,200 cords of wood valued at $289,800 were lost in the 99 jack pine stands as a result of this single outbreak. Average stand volume loss was 2.3 cords/acre and average standing value loss was $78/acre. Mortality accounted for most of the volume loss, though growth reductions also contributed. Though topkill was common, we discovered that the dead tops rarely affected the merchantable volume of wood within the tree. Interestingly, the greatest volume and value losses were concentrated in only a few stands. In fact, eight stands accounted for more than half the volume and value losses, even though these stands made up less than 25 percent of the area. In these eight stands, standing volume and value loss averaged 6.8 cords/acre and $237/acre, respectively.

Site and stand variables: We used statistical methods and modeling to relate patterns of tree mortality, topkill, growth loss and economic loss to stand inventory variables. We found that, as expected, stand age was a major factor affecting the vulnerability of trees, particularly when age exceeded 40 to 45 years. Basal area, a measure of tree density and size, and the abundance of suppressed trees and wolf trees (open-grown, full-canopied trees) were sometimes related to biological or economic impact but were less important than we expected (Conway et al., 1999c). These results may provide managers with the flexibility to set aside poorly stocked or overstocked stands for wildlife habitat or other non-timber uses without substantially increasing the vulnerability of the forest to JPBW impact. Other variables such as stand size and soil type did not have major effects on volume or value loss.

We were able to identify some important patterns we had previously not suspected. For example, there is a long-standing belief in the Great Lakes region and Canada that trees growing on low-quality sites experience more impact and greater economic loss. This relationship, however, had not been previously quantified. Our data consistently indicated that, in fact, trees on the better sites were more likely to be killed during a JPBW outbreak than trees on poor sites. We have several testable hypotheses to explain this pattern, which we hope to explore in the future. These results are important to managers who must prioritize stands for harvest or salvage and identify stands to be reserved for recreation or wildlife.

Lake States Jack Pine Budworm Decision Support System: Results from our work were used to develop the Lake States Jack Pine Budworm Decision Support System. The DSS runs in an ArcView platform, a software program used by all national forest managers and by many state resource management agencies. A stand-level growth-and-yield model projects the growth of jack pine stands for up to 30 years. The user selects the length of the projection period, the number of JPBW outbreaks that will occur and the area that will be affected by the outbreaks, and provides a price for jack pine. Standard inventory variables including stand age, basal area and site index are used to determine the accumulation of basal area and merchantable volume over time. Loss in basal area, volume and value (discounted into the future) due to JBPW impact is calculated for each stand. The DSS compares the growth, volume and value of stands at the end of the projection period with and without JPBW impact. Maps are produced to highlight high hazard stands, volume and value accumulation and loss, and other results. Tables and charts provide estimates of volume, growth, and age class and size distribution of the stands at the end of the projection period.

A user's manual was produced and the DSS was delivered to Hiawatha National Forest personnel in 1998. Some training and assistance were provided, and by late summer, the DSS was being used for forest planning and other management activities in the Hiawatha National Forest. We also provided summaries of our results and demonstrations of the DSS to personnel from the Huron-Manistee National Forest and the Michigan Department of Natural Resources. These agencies currently have internal problems with the quality of their GIS data that prohibit them from using the DSS. Once these problems are resolved, however, they will also be able to utilize the DSS.

Management Recommendations

Managers of state and federal lands are faced with increasing pressures to provide timber, fiber, wildlife habitat, recreation and other benefits from a limited area of forested land. Faced with these often conflicting goals, managers must efficiently allocate resources while ensuring that forests remain healthy and productive. Managers need information about the extent of losses caused by specific forest pests and silvicultural recommendations to minimize such losses.

In this project, we were able to quantify the tree mortality, topkill and growth loss that occurred as a result of a single JPBW outbreak. We then used economic modeling and growth-and-yield models to quantify this loss in financial terms. The spatial and temporal scale of this study exceeded that of any previous study of defoliator impacts in the Great Lakes region and represented the first time that empirical biological data had been used to directly assess financial impacts of a JPBW outbreak. Over the past several months, we have provided forest managers in Michigan with tables that show the standing volume and value losses for jack pine stands grouped by age class, site index and basal area. Managers can use these statistics to estimate potential losses and identify stands that should be harvested or salvaged. These data can also be useful in the forest planning process to ensure that forests are managed on a sustainable basis and are not overharvested.

The importance of evaluating both biological and economic impacts was borne out by our data. Some stands, for example, sustained high levels of tree mortality but relatively low volume or value loss. This occurred when mortality was concentrated on small or suppressed trees, while dominant or co-dominant trees in the same stand recovered. In this situation, mortality attributable to JPBW defoliation may be of little concern to a manager, perhaps even benefiting the forest by acting as a form of natural thinning.

We discovered that, although topkill was fairly common in these stands, the dead portion of the leader rarely extended far enough down the stem to decrease merchantable volume. On the other hand, our intensive analysis of radial growth, combined with historical reports of past JPBW outbreaks, leads us to predict that trees that were topkilled during this past outbreak may be most likely to die during the next outbreak. Topkill can be efficiently assessed by forest health specialists or managers during aerial surveys. If our predictions are accurate, then managers could quantify topkill and have a long lead time to plan harvests or other actions before another outbreak occurred.

One of the most important results of our project was the relationships that we identified between site or stand characteristics and the amount of biological or financial impact sustained by the stand. The variables we worked with, such as stand age, basal area and site index, are standard inventory variables that are available to any resource manager. Therefore, managers can use the relationships we developed and their own inventory database to prioritize stands for harvest or salvage, or to identify stands that should perhaps be designated for cover-type conversion or as wildlife habitat.

We determined that a non-linear relationship exists between tree age and the amount of mortality that occurs following a JPBW outbreak. Once trees reach 45 to 50 years of age, mortality increases dramatically. This result was not unexpected because jack pine is a fairly short-lived species. It is a concern, however, because many jack pine stands were established during the 1930s and 1940s and are now overmature and highly vulnerable to both biological and economic damage.

Basal area had less effect on stand vulnerability than we expected. Traditionally, managers have been encouraged to maintain well stocked jack pine stands and to avoid understocked and overstocked stands. We found, however, that understocked stands sustained relatively low rates of mortality, and that in overstocked stands, most mortality occurred on suppressed trees of little value. Therefore, the effect of basal area on value loss was not substantial. This may be welcome news to managers who can often regenerate jack pine stands more efficiently by seeding than by planting. Seeding may not result in the uniform spacing that typifies plantations, but our results suggest that variable spacing and tree density may not substantially increase losses to JPBW.

The relationship between tree mortality and site index was striking, consistent and the opposite of what we had expected. Traditionally, forest entomologists have assumed that jack pine stands growing on poor sites would be more vulnerable to damage during a JPBW outbreak than stands of similar age growing on better sites. This relationship, however, had never been tested. We found that mortality and value loss of older stands growing on good sites was three to four times higher than that of stands of similar age and basal area growing on poor sites. We have identified testable hypotheses to explain this pattern and hope to address this relationship further in subsequent research. In the meantime, however, we have provided forest managers with this information and urged them to incorporate this pattern into their planning process. For example, when a manager is attempting to prioritize stands for harvest and there are many overmature stands, it may be best to harvest the stands occupying relatively good sites first. Trees on poorer sites may be more able to tolerate or recover from JPBW defoliation and can be left standing longer without greatly increasing the risk of damage.

Technology transfer

Transfer of research results and new technology from scientists to land managers is an important component of any research project. We continue to provide our results to forest managers and forest health specialists in Michigan through traditional outlets including publications, workshops and training sessions. Perhaps more importantly, we were able to incorporate our results into the Lake States Jack Pine Budworm Decision Support System. This program is simple to learn and utilizes standard inventory variables and computer software that are or soon will be readily available to managers of state and federal forestland. Hiawatha National Forest personnel involved in the forest planning process are already using the DSS. In addition, the GIS maps produced by the DSS have proven to be a useful tool to explain the basis for harvest decisions or other actions to environmentalists, forest industry representatives and other special interest groups.

Relationship to the original SAPMINR report

Each year, losses to insects and pathogens typically exceed the amount of timber harvested in North American forests. Loss to forest insect pests was identified as a key concern in the original SAPMINR report. Most of these insects, however, are native species that are intrinsic components of these ecosystems. While accepting that these insects will continue to be present, researchers and managers can work together to identify silvicultural methods to reduce the damage they cause while maintaining healthy, diverse and productive forests. Results of our JPBW project should increase the overall health and productivity of Michigan's jack pine forests. Managers will be able to make more informed decisions and can more accurately assess the existing jack pine resource and how this resource may be affected in the future by JPBW outbreaks.

Additional funding and research:

The Hiawatha National Forest contributed in-kind support for this project by providing housing during the 1996 field season, maps and aerial photos, and up-to-date inventory, GIS and cost data. Additional funding to quantify JPBW impact was secured in 1997 from the Forest Health Unit, USDA Forest Service, Northeastern Area State and Private Forestry group in St. Paul, Minn. This funding enabled us to resurvey stands in the Raco Plains area in 1997 and 1998, and to begin establishment of permanent plots in selected stands. Our goals are to collect long-term data from these plots to monitor the fate of topkilled trees during the next JPBW outbreak, quantify the effects of multiple JPBW outbreaks over the course of a jack pine rotation and determine how management practices affect JPBW impact. Results from our project will also form the basis of future grant proposals to more fully evaluate the relationship between site quality and jack pine mortality, and to determine how JPBW defoliation may alter jack pine carbon allocation. Additional peer-reviewed articles based on the decision support system and optimal jack pine management are planned.

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