JAAKKO PÖYRY
JAAKKO PÖYRY CONSULTING, INC.

Forest Health

A Technical Paper for a
Generic Environmental Impact Statement
on Timber Harvesting and Forest Management
in Minnesota

Prepared for:

Minnesota Environmental Quality Board
658 Cedar Street
St. Paul, Minnesota 55155

October 1992

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November 6, 1992

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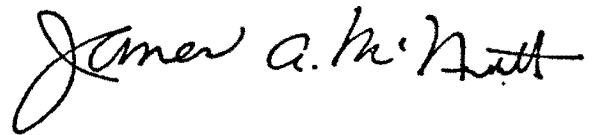658 Cedar Street
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Dear Dr. Kilgore:

Pursuant to the State of Minnesota's GEIS contract (No. 30000-18408-01) with Jaakko Pöyry Consulting, Inc., as formally executed on May 15, 1991, and amended with Supplement No. 1 on July 10, 1991, and Supplement No. 2 on July 27, 1992, the sixth task included preparation of technical papers. One of these papers, Forest Health, is hereby submitted for review and approval.

The material contained in this document is presented in accordance with the terms outlined in Attachment A to the base contract, Section III, Subsection F.

We look forward to a favorable review and approval of this work product in due course.

Respectfully yours,

James A. McNutt
Executive Vice President
and GEIS Project Manager

cc: Art Veverka
      Bob Dunn
      Doug Parsonson
      Alan Ek

SUMMARY AND CONCLUSIONS

Forests are presumed to be healthy when biotic and abiotic influences do not threaten the attainment of either current or future management objectives. Although specific aspects of forest condition can be quantified and measured objectively, assessing forest health depends in part on subjective evaluations and value judgements.

Insects and diseases are important components of the forest ecosystem; they are fundamental agents of change impacting long-lived communities. The effects of insects and diseases on forests in the Lake States include tree mortality, tip dieback or top-kill, loss of reproduction and regeneration, loss of tree form and reduced resistance to other stresses. These effects can be translated into impacts on human uses of the forest such as loss of productivity due to mortality, decay, reduced growth rates and increased risk to fire. In addition, insects and disease can impact the recreational and aesthetic aspect of forest resources. Pests and diseases can also affect wildlife habitat values. Fungal decay provides habitat by creating hollows in trees, and insect pest larvae are a source of food for many species. However, widespread pest outbreaks leading to high levels of tree mortality may also reduce the habitat values for other wildlife species. This is a particular problem where natural checks and balances controlling a pest population cease to function, or where a new pest is introduced and there are no natural controls to check its growth.

The risk to a forest stand of a pest attack or infestation (susceptibility) and the likelihood of damage if an attack occurs (vulnerability) are frequently related to stand age. Typically, as stands get older they become more susceptible to damage and are at greater risk of infestation. However, there are exceptions to this generalization where seedlings and young trees are preferentially attacked. Harvesting that requires multiple entries into a stand may also increase risk. For example, if care is not exercised, harvesting can damage residual trees, leaving them open to attack by both insects and diseases. Finally, atmospheric pollutants can weaken or stress trees, potentially increasing both their susceptibility and vulnerability.

The amount of damage incurred during outbreaks of insects or disease is generally related to stand attributes and environmental conditions. In some cases, especially for insects, pest populations can be regulated by the activities of biological control organisms including predators, parasites and pathogens. Stand and site-related factors associated with severe impacts vary substantially with the nature of the health problem. However, low vigor trees, particularly those stressed by drought, are most likely to be severely affected by insects and diseases. Species and age-class diversity within and

among stands may reduce impacts relative to large, continuous areas of similarly-aged host trees.

The purpose of this Technical Paper is to determine the possible effects of an increase in timber harvesting and associated management practices on forest health in Minnesota. To make this assessment, emphasis was placed on identifying the circumstances likely to change the proportion of susceptible/vulnerable age classes, and the circumstances that require multiple entry harvesting operations. For each covertype, a 10 percent change in susceptible or vulnerable area by age class (0 to 40, 40 to 50, 50 to 60, 60 to 70, >70 yrs), was established as the threshold to determine the minimum change needed to significantly affect susceptibility or vulnerability to most forest diseases. This percentage is also considered to be the minimum level of change that is detectable above naturally occurring variation. The data from the second harvest scenarios described in the Maintaining Productivity and Forest Resource Base technical paper (Jaakko Pöyry Consulting, Inc. 1992a) were used as a basis for determining changes in age class structure and associated changes to the state's forests susceptibility and vulnerability to insect pests and diseases.

In general, increased harvesting will tend to shift the age-class distribution of forest stands toward younger ages. When compared with the older stands they replace, younger stands are usually more vigorous and are typically more resistant to attack and are better able to recover following an attack. Increased harvesting will tend to reduce incidence of many insect pests and diseases that are favored by older forests. Insect species in this category include spruce and jack pine budworm and two-lined chestnut borers. In addition, diseases such as white trunk rot of aspen are also likely to be reduced. Other diseases will probably decrease in the short-term, but may ultimately increase as a result of increased intensity of timber harvesting, including cankers and decay of upland hardwoods and oak wilt.

In contrast, the incidence of some insect pests, such as white pine weevil, are likely to increase as a consequence of increased harvest levels. This is due to an increase in acreage of susceptible younger stands. The incidence of some diseases are also likely to increase, including *Diplodia* shoot blight and canker, and *Scleroderris* canker of red pine. Some of the predicted increases in susceptibility and vulnerability are based on the assumptions that an increase in timber harvesting would substitute young, more susceptible stands of pine species to replace older stands that have been cut; changed management objectives including longer rotations and hence more susceptible/vulnerable age classes of other forest types; and increased use of thinning and selection harvests that will increase the risk of damage to retained trees.

Mitigation alternatives focused on developing strategies to prevent pest buildups, to monitor and plan responses, and to apply stand level mitigations. Strategies discussed include:

- monitoring and, if required, manipulating age class distributions of forest type groups to manage changes in susceptibility and vulnerability associated with changes in age class;

- promote operator training and introduction of equipment that will reduce the level of damage to trees retained after thinning or selective cutting of a stand;

- more ownerships should be involved in monitoring pest populations;

- Integrated Pest Management Strategies for the major pests should be developed; and

- strategies to increase the use of MNDNR guidelines for pest management should be implemented.

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ACKNOWLEDGEMENTS

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INTRODUCTION

The purpose of this Technical Paper is to assess the impact of timber harvesting and management activities on forest health. The specific objectives have been defined as (MNEQB Final Scoping Decision 1990):

Forest Health. The management of forests should be undertaken so as to ensure that they are sustained in a healthy condition over long periods of time, recognizing that endemic pest conditions will be present. Considering previously specified timber harvesting levels and looking at timber harvesting and management activities statewide:

1. *What impact does timber harvesting and management have on the change in risk of disease and insect infestations to Minnesota's forests?*

2. *To what extent are changes in the risks of insect and disease infestations specific to a particular forest landowner class, geographic region, tree species or forest type?*

1.1
Issue Description

Forests are presumed to be healthy when biotic and abiotic influences do not threaten the attainment of either current or future management objectives. Although specific aspects of forest condition can be quantified and measured objectively, assessing overall forest health depends in part on subjective evaluations and value judgements. For example, under the National Forest Health Monitoring (NFHM) program, forest health is considered with respect to both naturally occurring factors such as fire, forest pests, forest succession, site, drought, and weather extremes, as well as unnatural biotic and abiotic factors including introduced pests, air pollution, and changes due to global warming. The USDA Forest Service's Forest Pest Management Program, however, considers forest health to be related to forest ecosystem resilience and productivity relative to a specified set of values, needs, and expectations. Thus, forest health can be defined by different standards which relate to differing management objectives for particular forested areas.

Although endemic populations of both insects and pathogens are important components of forest ecosystems, outbreaks of pests can result in substantial ecological change and loss of timber production. Outbreaks can be triggered by natural processes such as plant stress induced by moisture and nutrient depletion, and by adverse climatic conditions. Aspects of global change such as air pollution and global warming may also affect forest health. In addition

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to these factors, timber harvesting and forest management activities can also change the susceptibility and vulnerability of stands. Changes can be positive, i.e., a lessening of risk, as well as negative, i.e., an increasing of risk. This paper assesses changes to risk of insect and disease infestations in Minnesota's forests under current and potentially more intensive levels of timber harvesting and forest management activity.

Insect and disease problems in Minnesota's forests have been documented in reports written by the Minnesota Department of Natural Resources (MNDNR), Forest Insect and Disease Management Unit; and the USDA Forest Service, State and Private Forestry and North Central Forest Experiment Station, St. Paul, MN. This paper includes a brief review of the important threats to forest health in Minnesota to provide the context within which changes induced by different harvest levels can be assessed. The review is supplemented by appendices (A—insects; B—diseases) that provide more extensively documented and detailed discussions of effects of insects and diseases on trees and forest stands.

Susceptibility and vulnerability of a stand is often dependent on the interactions of a range of biotic and abiotic factors. These factors, and the relationships between them and the stand, can be changed by timber harvesting and forest management activities. Many of these changes occur at a microscale and therefore are below the level of resolution specified for the GEIS. However, two factors which can be indicators of change in susceptibility and vulnerability—changes to the age class distribution of a covertype, and increasing use of multiple entry harvesting systems—can be detected at a statewide level of resolution.

Stand Age
Some insect species and diseases preferentially attack their host species during particular stages of stand development. Therefore, for affected covertypes, a change in age class distribution can be interpreted as a change in susceptibility and vulnerability (either an increase or decrease).

The technical paper, Maintaining Productivity and the Forest Resource Base (Jaakko Pöyry Consulting, Inc. 1992a) provides an analysis of the projected changes in age class distribution under the three timber harvesting scenarios examined in the GEIS. The paper also discusses trends in age class distribution that have occurred since accurate records have been kept. The conclusions drawn from that analysis are that Minnesota's forests are aging. This is explained by the fact that, for most covertypes, timber volume growth has exceeded removals (harvesting) and mortality (fire, insect and disease, etc.).

The increased levels of harvest experienced in the state in more recent times have reduced the age imbalance for some species, notably aspen. However,

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large areas will continue to move into older age classes. This shift has important implications for forest management. Some covertypes, such as the white pine or maple-basswood types, are comprised of species that are comparatively longer lived. Older stands of these more long-lived species typically develop rich species diversity when compared to the pioneer covertypes. These more complex communities are less prone to damaging outbreaks of pests and diseases. Pest populations are typically kept in check by a range of natural controls including native predators and parasites. However, this comparatively stable situation can be disrupted when exotic pest species are introduced. Dutch elm disease and the Asian and European gypsy moth are good examples of such exotic pests.

In contrast, covertypes such as aspen and jack pine are comprised of species that are comparatively short-lived; a characteristic of many pioneer species. As these species grow older they lose their vigor and become increasingly susceptible and vulnerable to attack by pests and diseases.

Multiple Entry Harvesting Systems
Silvicultural systems requiring more frequent entry into the stand can increase stand susceptibility. These multiple entry harvesting systems include systems used for uneven-aged stand management and also those used for thinning. Use of such systems, where a proportion of the stand is harvested leaving the remainder, can result in damage to the residual stems. Damage to the bark can attract insects and provide an entry point for pathogens. Therefore, an increase in the area treated by such systems can be interpreted as an increase in the susceptibility of affected areas.

This paper has addressed these issues at a macro or regional/statewide scale in keeping with the level of resolution specified for the GEIS. However, site-specific conditions, which would only be assessed at the microscale, can be the major factors that determine susceptibility and vulnerability, and therefore may significantly alter these assessments of impacts and consequently the most appropriate mitigations.

**1.2
Sources of Data**

The analysis has been undertaken using outputs from the forest change and scheduling model reported in the Maintaining Productivity and Forest Resource Base technical paper (Jaakko Pöyry Consulting, Inc. 1992a). The Harvesting Systems and Silvicultural Systems background papers (Jaakko Pöyry Consulting, Inc. 1992b,c) were also consulted for background materials for these subject areas. Other sources of data include USDA Forest Service reports and draft copies of the *Forest Development Manual* and the *Insect and Disease Management Guidelines*, both authored by MNDNR

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personnel. These documents contain specific references to Minnesota conditions. Other references included silvicultural and pest management manuals, literature in scientific, peer-reviewed journals, and major textbooks (e.g., French and Cowling 1975, Sinclair et al. 1987).

The relevant literature pertaining to this subject area has been summarized for both insect and disease pests. These are presented as appendixes A and B, respectively. The literature is cited extensively in these appendixes. The remainder of this paper only cites the literature directly quoted.

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EXISTING ENVIRONMENT

2.1
Introduction

This review of the health status of Minnesota's forests is based on the sources of background information as described above. This information was used to determine the most important forest health problems in Minnesota. To aid in the synthesis and presentation of information, forest tree species were considered as broad forest covertype groups that parallel the FIA covertypes (table 2.1). These groupings were also used in later parts of this analysis.

Specific insect pests and diseases are identified for each group. In some cases forest health problems are uniquely associated with specific species. In these circumstances that species is discussed separately from the remainder of the group.

2.2
Current Productivity Losses Due to Forest Health Factors

The most recent forest inventory and analysis (FIA) of Minnesota's forests was initiated during the late 1980's and is currently being summarized. Information on timber growth, removals and mortality was obtained from the final but unpublished draft of *Minnesota Resource Statistics 1990* (Miles and Chen n.d.). Data from this report summarized average net annual growth, average annual removals, and average annual mortality of growing stock and sawtimber (all from 1977–89) (figures 2.1 and 2.2). Removals are defined as the volume of sound wood in growing-stock or live sawtimber trees removed annually for forest products (including roundwood products and logging residues) and unutilized trees removed from the commercial forest land classification by land use change. Mortality is presented as the average annual mortality, including that attributed to insects and diseases, and expressed in volume of sound wood in growing-stock or sawtimber trees. Total average annual mortality of growing stock is 219 million cubic feet and

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54 percent of the mortality is attributed to insects and disease (figure 2.1). Total average annual mortality of sawtimber is 452 million board feet and 57 percent is attributed to insects and disease (figure 2.2). Twenty-two percent of the volume of mortality is caused by *other or unknown* factors which may also be related to insect and disease problems. The earlier 1977 FIA survey data revealed similar trends, when 62 percent and 60 percent of the annual mortality of growing stock and sawtimber, respectively, was attributed to insects and disease. This is also consistent with data summarized in the Maintaining Productivity and Forest Resource Base technical paper (Jaakko Pöyry Consulting, Inc. 1992a). These chronic losses significantly reduce the volume of timber available for commercial harvest.

Table 2.1. Forest type groups used in synthesis of forest health information in relation to timber harvest.

Forest Type Group	FIA Covertypes	Major Constituent Species	
		Common Name	Species
Aspen-birch	Aspen Birch Balsam poplar	Paper birch Balsam poplar Bigtooth aspen Quaking aspen	*Betula papyrifera* *Populus balsamifera* *Populus grandidentata* *Populus tremuloides*
Black Spruce	Black spruce	Black spruce	*Picea mariana*
Lowland Conifers	Northern white cedar Tamarack	Balsam fir Tamarack Black spruce Northern white cedar	*Abies balsamea* *Larix laricina* *Picea mariana* *Thuja occidentalis*
Lowland Hardwoods	Elm-ash-cottonwood	Red maple Paper birch Black ash American elm	*Acer rubrum* *Betula papyrifera* *Fraxinus nigra* *Ulmus americana*
Pine	Jack pine Red pine White pine	Jack pine · Red pine White pine	*Pinus banksiana* *Pinus resinosa* *Pinus strobus*
Spruce-Fir	Balsam fir White spruce	Balsam fir White spruce	*Abies balsamea* *Picea glauca*
Upland Hardwoods	Oak-hickory Maple-basswood	Sugar maple Yellow birch White oak Northern pin oak Red oak Basswood	*Acer saccharum* *Betula alleghaniensis* *Quercus alba* *Quercus ellipsoidalis* *Quercus rubra* *Tilia americana*
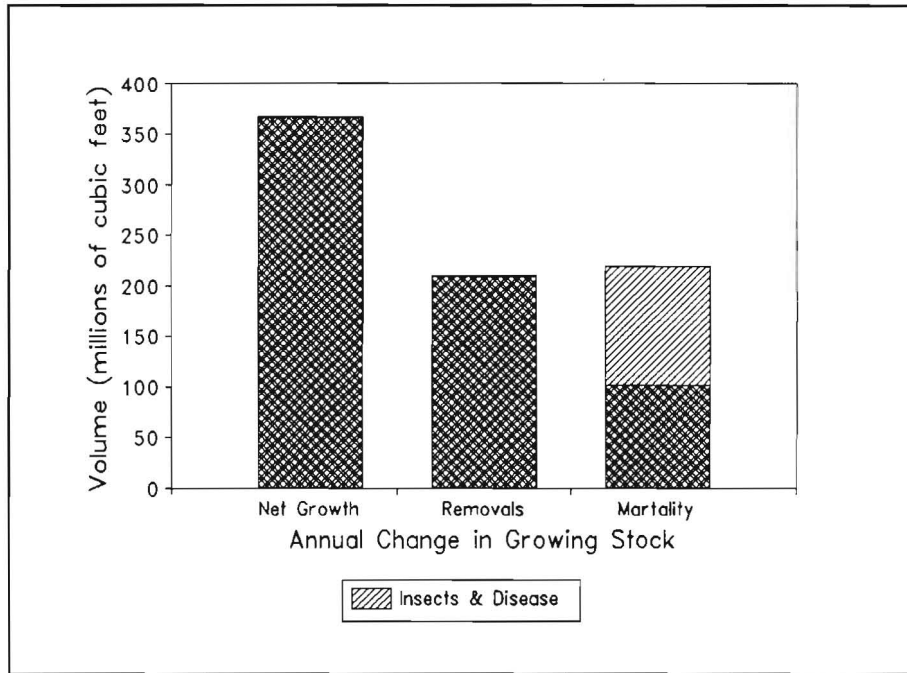
Figure 2.1. Annual changes in growing stock in Minnesota forests during the period 1977–89. (Source: Miles and Chen n.d.)
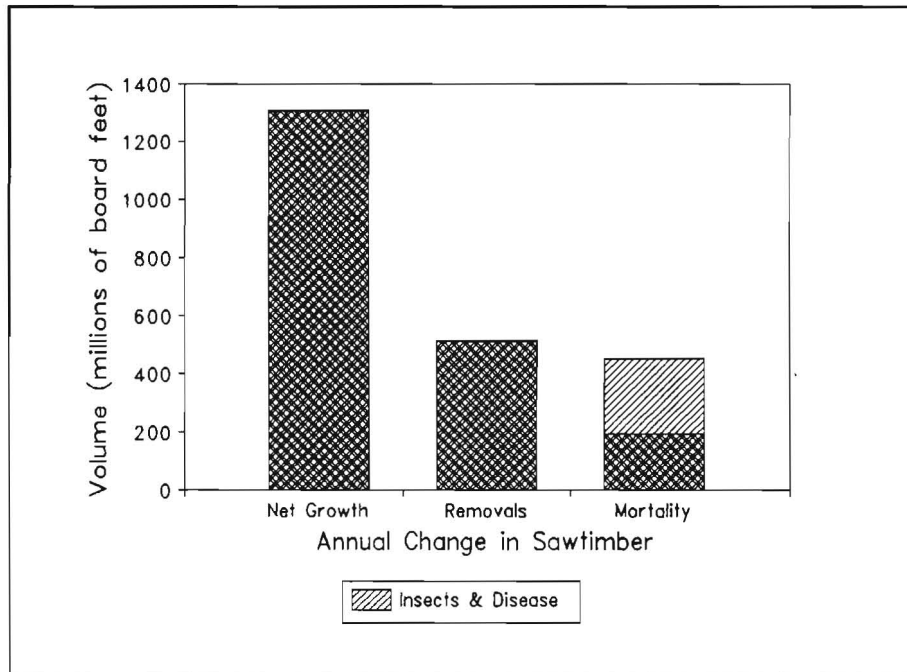
Figure 2.2. Annual changes in sawtimber volume in Minnesota forests during the period 1977–89. (Source: Miles and Chen n.d.)

2.3
Forest Health Management in Minnesota

Forest health management in Minnesota has two elements: (1) monitoring to detect and monitor pest population buildup and progress, and to identify causes of mortality; and (2) preparation and implementation of guidelines covering all aspects of the management, harvesting and regeneration of individual species and covertypes.

2.3.1
Monitoring

In recognition of the significance of the losses of growing stock and sawtimber to insects and disease as described above, two new programs have been initiated to increase the accuracy and quantity of data that describe the health of Minnesota's forests. In 1990, a format was developed to standardize *damage codes* reported by Forest Inventory and Analysis (FIA) field crews. The new system will improve the accuracy of future FIA data describing mortality caused by insects and disease. Standardized codes and training packages and an improved method of determining causes of mortality are all parts of the new system. Minnesota is the first state to use this new system, which will subsequently be implemented throughout the USDA Forest Service north central region.

The second program, Forest Health Monitoring (FHM), is a cooperative venture between the Environmental Protection Agency, the USDA Forest Service, and state foresters. Two goals of FHM are to (1) detect unexpected changes in forest conditions and coordinate an evaluation of these changes at the multistate level, and (2) improve the efficiency and effectiveness of pest management and land management decisionmaking processes. The main components of this program are a network of detection/monitoring plots, and development of a standard collection and reporting system for forest pest conditions.

With the advent of these two programs, knowledge of the status of the health of Minnesota's forests is expected to improve. The FIA pest data and FHM data should serve as major references for future evaluations of the health of Minnesota's forests.

2.3.2
Management Guidelines

The MNDNR, as well as the USDA Forest Service, have been developing a range of guidelines for forest practices which are intended to reduce likelihood of pest attack and the likelihood of damage should an attack occur.

These guidelines, which specify cultural methods for control, can be combined with direct methods of control as key elements of an overall strategy for pest control. This strategic approach is termed *Integrated Pest Management* (IPM). IPM uses a combination of cultural, biological, and chemical and/or mechanical techniques to achieve economical control of pests in an environmentally sound manner (MNDNR 1990). The MNDNR has taken the considerable body of work carried out by the USDA Forest Service, and has drawn on local research and experience, to produce guidelines that relate specifically to Minnesota conditions.

Guidelines have been produced by the MNDNR for most of the commercial forest types and are designed to be applied at an individual stand level, after modification to take into account specific stand conditions. Guidelines have been developed for the following forest types (MNDNR 1990):

- white pine,
- red pine,
- jack pine,
- spruce-fir,
- black spruce,
- white spruce,
- tamarack,
- northern white cedar,
- aspen,
- paper birch,
- oak,
- lowland hardwoods,
- central hardwoods,
- northern hardwoods, and
- black walnut.

At a more general level, the MNDNR has identified preventative measures for forest health that reflect IPM principles (MNDNR 1990):

1. Consult with regional insect and disease specialists in future stand management planning, or when problems occur in established stands.
2. Check all stands routinely for insects and disease. Promptly remove, destroy, or chemically treat infested material where economically feasible.
3. Utilize regeneration methods that reduce or eliminate insect and disease potential for attack of young seedlings. See specific recommendations by type.
4. Favor insect and/or disease resistant species or varieties.
5. Avoid replanting susceptible species in areas of historical insect and/or disease problems without an evaluation of cause.
6. Do not mix species that have common insect and disease problems.

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7. Match tree species to the planting site.
8. All management practices must be aimed at promoting stand vigor:
   a. use proper planting techniques,
   b. manipulate rotation age, and
   c. maintain proper stand density.
9. Avoid planting in frost pockets.
10. Avoid wounding growing stock during thinning and/or harvesting operations.
11. Diversify species whenever possible.

2.3.3
Pest and Disease Management in Minnesota

The guidelines developed by the MNDNR for pest and disease control are integral parts of the IPM strategy. These cultural methods are supplemented by direct control (insecticides) and biological methods.

Silvicultural or Cultural
Pest control strategies have primarily focussed on cultural measures. Cultural strategies typically include physical manipulation of stands, often by harvesting to either remove infected trees, or to promote vigorous growth in trees thereby reducing opportunities for pests to become established. In common with many silvicultural problems, health-related measures are typically employed only if low cost solutions are available. This reflects the comparatively low timber values of many of the more vulnerable and susceptible stands, and the often extensive nature of outbreaks. Many ownerships are simply unable to justify the expense of pest control measures.

Many of the guidelines are expressed in terms of practices or situations to be avoided so that no records of relative success or failure of the guidelines are available. Other guidelines prescribe methods of timber harvesting that also achieve objectives of pest and disease control. The guidelines for control of dwarf mistletoe in black spruce are a good example of this type. The recognition of the potential for pest and disease problems and the application of the most appropriate cultural measures often requires a stand level as well as forestwide analysis (MNDNR 1990). This level of professional input is available on state, federal, county and forest industry lands, but is less available or not available for NIPF lands.

Direct Control
Direct control methods involve spraying to kill pests. Cost and the potential for controversy surrounding possible unintended side effects limits the choice of direct control methods that can be applied. The Water Quality and Fisheries Technical Paper (Jaakko Pöyry Consulting, Inc. 1992d) discusses the concerns regarding possible effects of insecticides on nontarget aquatic

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species. There are no data available on the use of insecticides in Minnesota because of the low level of use in commercial forests. Insecticides might be used in the event of future gypsy moth or spruce budworm attacks. Possible insecticides include *Bacillus thuringiensis* (B.t.), a microbial insecticide used to control lepidopteran and dipteran pests in forests. Dimilin® (difenbenzuron) has been used in Maryland forests for control of gypsy moth.

Biological Control
Predatory, parasitic and pathogenic organisms often contribute significantly to regulation of forest insect pest populations. Classical biological control is typically defined as the importation and release of native or exotic predatory, parasitic or pathogenic organisms (e.g., natural enemies) to control a targeted pest. Other biological control strategies include augmentation of existing populations of natural enemies or modification of habitat to favor natural enemies. Successful biological control is often constrained by lack of knowledge of the attributes of the pest, the natural enemy and their interaction. Acquiring such knowledge often entails intensive research efforts.

However, biological control has been implemented successfully in Minnesota forests for control of larch sawfly (see appendix A). Natural enemies and potential biological control agents of several forest insect pests including other sawfly species, spruce and jack pine budworm and forest tent caterpillar have been investigated. A recent study conducted in Minnesota with cooperation from the MN Department of Agriculture involved successful establishment of an exotic parasitoid wasp in anticipation of gypsy moth establishment (see appendix A).

Biological control strategies are often compatible with other pest control or integrated pest management strategies. Biological control can often contribute to long-term pest management and seldom results in adverse environmental consequences. The potential exists to incorporate more biological control into pest management if benefits can be demonstrated to justify costs of research and implementation.

2.4
Pests and Underlying Forest Health Factors

As has been discussed elsewhere, the relative *health* of a forest stand is influenced by many biotic and abiotic factors. Many of these factors are related to the site, genetics, or to ongoing pest problems. These are important factors, and must be considered by managing agencies when developing holistic forest health policies.

However, most of these factors are more or less independent of the level of timber harvesting and forest management activities. Site factors such as soil pH are mostly independent. Tree genetic factors are typically independent, although they can be changed such as where genetically improved clonal material is used to replace native stock when replanting a site. The occurrences of some insects and diseases are linked to these factors. These factors and the pests that are linked to them have been fully reviewed in appendixes A and B. Finally, some important pest species are neither advantaged nor disadvantaged by the level of timber harvesting and forest management activities.

Because these background factors are largely independent of the level of timber harvesting and forest management activities, they are outside the scope of the GEIS (see section 1). Therefore, this section and subsequent sections of the paper are focussed on insects and diseases that are likely to respond to changes in the level of harvesting. However, in recognition of their importance as underlying factors affecting forest health, this section includes a synthesis and discussion of these background factors for relevant forest types.

2.4.1
Aspen-Birch

Specific Pests Potentially Affected by Harvesting
Forest Tent Caterpillar
Under current conditions, forest tent caterpillar outbreaks occur at 6- to 16-year intervals and persist for three to four years. Some pockets may sustain defoliation for five to eight years or longer. Outbreaks are characterized by extensive, widespread areas of defoliation. Growth of aspen trees is impacted by defoliation; with the magnitude of reduction proportional to severity and duration of defoliation. Tree mortality is usually low, and growth rates typically recover within a few years. Trees with low vigor or stressed trees may be affected more severely than healthy trees. Mortality is often associated with overmature trees, drought, or where high water tables preclude normal root development. Larvae are abundant during outbreaks and may provide food for birds, bears and small mammals. Recreation and aesthetic values may be negatively affected during outbreaks. This is caused by the unattractive appearance of large areas of defoliated trees, coupled with annoyance caused by larvae, frass, and swarms of sarcophagid flies that parasitize larvae.

White Trunk Rot
White trunk rot is the primary cause of heartrot of aspen in Minnesota. This disease is the major cause of loss of wood volume in aspen. A link between increasing age of aspen and increasing incidence of rot has been clearly

established. There is conflicting information on the relationship between site and disease incidence. In general, better sites (deep, sandy silts or loams) are likely to have less decay than poorer aspen sites. Variation in susceptibility to decay among different aspen clones has also been shown.

Hypoxylon Canker
Losses due to Hypoxylon canker in Minnesota, Wisconsin, and Michigan are currently estimated to be $4 million annually, and in 1971, the average proportion of live aspen trees infected was 12.1 percent. Aspen in all age classes are susceptible; mortality, however, is usually greater in young trees. High-vigor and low-vigor trees are susceptible to infection. Low-density stands have proportionally more infection than high-density stands. Susceptibility to infection varies by clone.

Armillaria Root Rot
Currently, *Armillaria* root rot is a pest on aspen of all ages. It usually is considered to cause chronic losses, but it can cause severe and acute losses following physical disturbance of the soil by logging or scarification. Research in northern Minnesota has shown that under very short rotations (four 4-year rotations), significant increases occurred in the proportion of sprouts infected with *Armillaria*. The interval between harvests in this trial was far shorter than those used for wood production. However, the results may indicate an increased potential for *Armillaria* following repeated harvests at the longer rotations commonly in use. If soil compaction and rutting occurs during the harvest, root injury may occur and increase the incidence of *Armillaria*.

Background Factors and General Considerations
Maintenance of healthy aspen stands requires attention to several factors including soil type, stocking, and clonal varieties. The best sites for aspen are porous, loamy, well-drained soils. Dry, sandy soils, and clay soils that are poorly drained or have a high water table are generally poor sites. Pest problems are likely to be magnified on poor sites. Regenerating aspen on low site index (<50) sites is likely to produce stands more susceptible to pests than regenerating on higher site index (>70) sites. Site selection is very important for maintaining healthy birch. Regenerating birch on poor sites (site index <55) will encourage susceptibility to drought followed by infestation by the bronze birch borer. Regenerating birch on south and west slopes can cause root death and mortality as the soil temperatures rise following harvesting. Harvesting operations may cause soil compaction and injury to the root systems of aspen, especially if harvesting occurs during wet seasons. This may impair potential for resprouting and result in poor stocking. Poorly stocked stands are more susceptible to insect and disease problems. Regenerating aspen clones that are highly susceptible to pests degrade aspen health. If aspen stands with more than 25 percent of the trees infected with Hypoxylon are naturally regenerated, the site will continue to

be occupied by disease-susceptible aspen clones. If repeated short rotations are chosen as the method of harvest, *Armillaria* root rot may intensify and severely reduce the productivity of aspen.

2.4.2
Black Spruce

Specific Pests Potentially Affected by Harvesting
Dwarf Mistletoe
It has been estimated that in Minnesota, as much as 11 percent or 154,000 acres of black spruce timberlands are infected by eastern dwarf mistletoe. Results from recent MNDNR pest surveys indicate that 22 percent of the black spruce in Koochiching County is infected with the disease to various degrees. The impact of this disease can best be reduced through careful adherence to harvest, site preparation, and regeneration guidelines outlined by the MNDNR insect and disease management guidelines.

Background Factors and General Considerations
Site selection, rotation age, site preparation and regeneration methods are very important considerations when managing for healthy black spruce. Root and butt rot caused by *Inonotus tomentosus* may be a serious problem if regeneration of black spruce is encouraged on acidic (pH 4 to 5) soils, soils low in nutrients or moisture holding capacity, or where root depth is limited by shallow soil or a hard pan. Root and butt rots are more common in upland stands after age 60 to 70. Stands infected with eastern dwarf mistletoe must be harvested and regenerated with disease management as a high silvicultural priority or this disease will continue to infest the stand, thereby severely reducing the health of black spruce.

2.4.3
Lowland Conifers

Specific Pests Potentially Affected by Harvesting
Balsam fir is a component of this type, and for a discussion of significant diseases of balsam fir, refer to the spruce-fir section (2.4.6). No other diseases of lowland conifers are discussed because their incidence is either unknown or of little consequence.

2.4.4
Lowland Hardwoods

Specific Pests Likely to be Affected by Harvesting
Gypsy Moth
Some species, particularly birch, could potentially be impacted if gypsy moth becomes established in Minnesota. However, that impact is independent of

the level of harvest. This pest is discussed more thoroughly in the upland hardwood section (2.4.7).

Dutch Elm Disease
Dutch elm disease is widespread throughout the state of Minnesota. Prompt removal and utilization of diseased elm wood is currently recommended in urban areas to minimize the impact of this disease. Such measures are unlikely to be feasible in forested areas. Thus, the rural elm resource will decline, and perhaps the incidence of this disease as well when elms are less common in the landscape.

Background Factors and General Considerations
There are relatively few major pests of lowland hardwoods. Selective harvesting always results in injury to retained trees. The resulting wounds may be infection courts for trunk rot of lowland hardwoods, especially red maple. Currently, forest insects have a minor impact in lowland hardwood forests.

2.4.5
Pine

Specific Pests Likely to be Affected by Harvesting
White Pine Weevil
Damage from white pine weevil results in growth and productivity loss and distortion of tree form. Larval feeding in terminal shoots kills two to four years of terminal shoot growth, resulting in crook, fork and acute branch angles. Repeated attacks on trees may so disrupt the development of regrowth that it becomes suppressed, eventually dying out of the stand. Weevil attacks before trees reach 20 to 25 feet in height typically destroys tree form, downgrading trees or eliminating their use for sawtimber. Volume loss due to reduced height, defects and taper may be significant. White pine weevil problems are generally more severe in northern Minnesota than in the central or southern regions of the state.

White Pine Blister Rust
White pine blister rust is most severe in northern Minnesota (see climatic hazard zone map appendix B). Infected trees (especially young trees < 10 years old) may develop cankers that girdle and kill them. Reproduction may become so heavily infected in high hazard zones that regenerating white pine may not be feasible unless resistant nursery stock is available.

Jack Pine Budworm
Outbreaks of jack pine budworm occur at roughly 10-year intervals and persist two to four years. Severe defoliation may result in the death of stressed and low-vigor trees. In well-stocked stands, mortality is generally low; however, substantial growth loss and loss of tree form due to top-kill

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are typical. In Minnesota, growth losses have ranged from zero to 100 percent, depending on duration and severity of defoliation. Damage to cones and mortality of understory reproduction may affect jack pine regeneration. Poorly stocked stands, overmature stands and low vigor stands are most susceptible and vulnerable to infestation of this pest.

Jack Pine Stem Rusts

There are four major rusts of jack pine in Minnesota. Alternate hosts are required for completion of the life cycle of these rusts; pine-oak rust requires oak in the red oak group, sweetfern rust requires sweetfern, Comandra rust requires false toadflax or other species of *Comandra*, and stalactiform rust requires cowwheat or Indian paintbrush. All of these rusts cause galls or swellings on jack pine seedlings or branches and galls or cankers on the main stem. Damage includes growth reduction, provision of an entry court for decay fungi and insects, and death by girdling or wind breakage.

Armillaria Root Rot

Armillaria root rot is principally a problem on sites converted from hardwoods to pine. *Armillaria* will use hardwood stumps (such as oak and aspen) as a food base while it extends its rhizomorphs through the soil, infecting live red pine roots. As a result, hardwood sites that have been harvested and are being planted to red pine can support a high population of *Armillaria* and pose a threat to red pine.

Diplodia Shoot Blight and Canker, Scleroderris Canker

There are certain aspects of pest control related to site selection in pine plantations. The incidence of these diseases is closely linked to site selection and is independent of the level of harvesting. The diseases are:

- *Diplodia shoot blight and canker* is most threatening to red pine growing on very droughty sites. Infection of shoots often leads to branch dieback and stem cankers. Trees may be killed or deformed.

- *Scleroderris canker* is most prevalent on young (< 10 years old) red pine growing in frost pockets or in bowl-shaped depressions in the landscape. This disease has strict environmental requirements for infection and disease development to occur. *Scleroderris* canker is most likely to occur in forest areas in northern Minnesota or at high elevations where summers are cool and the frost-free period is less than 90 days. Infection may result in branch or tree mortality. The European strain of *Scleroderris* is considered to be much more virulent than the native strain. If the European strain were to be introduced into Minnesota (it is currently in upstate New York), its control would be likely to require much closer adherence to management guidelines. However, there is

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considerable uncertainty in predicting behavior of a pest until it is established.

Incidence of *Diplodia* shoot blight and canker and *Scleroderris* canker on young (<40 years old) red pine may increase if the areas planted to red pine are not carefully chosen. Red pine planted on droughty sites or sites with a history of *Diplodia* being present will be most susceptible to this disease. Red pine planted in frost pockets or in northern areas or at high elevations where summers are cool and the frost-free period is less than 90 days will be most susceptible to *Scleroderris* canker. Both of these pests are not major problems on older red pine.

Ips Bark Beetle

Ips beetles are secondary borers and usually breed successfully only in severely stressed or felled trees and slash. If populations build to high levels, even healthy trees can be successfully attacked and killed. In Minnesota, mortality from Ips beetle attack has generally been associated with plantations or stands where slash or windthrown trees contributed to population build-up. The 1988 drought caused widespread tree stress and resulted in relatively severe mortality from Ips attack. Population build-up and significant tree mortality can be largely controlled in most cases by following guidelines for slash and log treatment developed by the MNDNR. Under normal circumstances (e.g., no drought), Ips beetle mortality is likely to be spotty and confined to a relatively small number of acres in any location. Trees damaged by wind, lightning, flooding, defoliation or pathogens may be at risk from Ips beetle attack.

Background Factors and General Considerations

Site selection and regeneration methods are extremely important when attempting to grow healthy white pine. Injury and mortality from white pine blister rust and white pine weevil can be minimized through careful site selection and regeneration as outlined in the MNDNR insect and disease management guidelines. Areas in northern Minnesota (see climatic hazard zone map in appendix B) are most susceptible to white pine blister rust. Site selection is also important for growing healthy red pine. Incidence of *Diplodia* shoot blight and canker is likely to be higher on very droughty sites or sites with a history of *Diplodia*. Incidence of *Scleroderris* canker can be related to site and is more likely to become established in low depressions or frost pockets. *Sirococcus* shoot blight is most serious in uneven-aged stands. Regeneration of red pine adjacent to a *Sirococcus*-infected overstory will perpetuate a disease-infested red pine stand.

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2.4.6
Spruce-Fir

Specific Pests Likely to be Affected by Harvesting
Spruce Budworm
Severe growth loss and mortality can occur during outbreaks of spruce budworm. Budworm outbreaks can last 7 to 10 years or more and may cover vast geographic areas. Previous outbreaks in Minnesota have resulted in volume losses of 24 to 67 percent of growing stock and extensive top-kill. Seed and cone production is often severely reduced and decreased vigor resulting from defoliation can predispose trees to attack by secondary organisms. Budworm-induced mortality, combined with increased breakage and windthrow in defoliated stands, has historically been followed by severe wildfires. Impacts of spruce budworm depend on species composition and tree age. Balsam fir and mature or overmature trees are more vulnerable when attacked and sustain higher mortality than spruce species or younger trees. Site conditions also affect stand vulnerability; for example trees on abnormally wet or dry sites are most affected by defoliation.

Trunk, Root and Butt Rots of Balsam Fir and White Spruce
There are several fungi that cause root, butt, and trunk decay of balsam fir and white spruce. *Armillaria* spp. and *Haematostereum sanguinolentum* may cause root, butt and trunk rot of balsam fir and are more prevalent in stands more than 50 years old. *Inonotus tomentosus* causes root rot on white spruce and is most prevalent on sites where soils are very acidic (pH 4 to 5) and low in nutrients and moisture-holding capacity. Reports from Ontario put losses from these pests in older stands (>65 years) at about 15 and 35 percent of the gross merchantable volume for white spruce and balsam fir, respectively.

Background Factors and General Considerations
Rotation age, age class and species distribution, and site selection are all important factors to consider when growing healthy spruce-fir. Spruce-fir over 50 years old may become infected with numerous root, butt and trunk rots that rapidly decrease the merchantable volume. Risk of spruce budworm attack increases if an increase in harvesting leads to regeneration of the spruce-fir type over large contiguous areas and mixed species are not encouraged (hardwoods with conifers), Root rot may pose a threat to the health of white spruce where sites regenerated to spruce-fir are acidic (pH 4 to 5) and low in nutrients and moisture-holding capacity.

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2.4.7
Upland Hardwoods

Specific Pests Likely to be Affected by Harvesting
Two-lined Chestnut Borer
This wood-boring insect generally attacks stressed and weakened oaks, particularly red oak. Under normal circumstances, two-lined chestnut borers only attack the inner bark of low-vigor trees and trees with broken branches. However, periods of drought, defoliation, ice storm damage, livestock grazing or other stress can predispose trees to attack. For example, following the 1988 drought, oak mortality in Minnesota ranged from 1 to 20 percent and reached 70 percent in some stands in central Minnesota. Stands previously defoliated or those infected with Armillaria or on droughty sites were most severely impacted by this pest. Mortality, dieback and loss of vigor can result in loss of acorn production and a loss of regeneration from stump sprouting.

Younger trees are generally more vigorously growing and have more starch reserves than older trees. They are therefore less affected by drought and other environmental stress and presumably less susceptible to severe damage by two-lined chestnut borer. If younger trees experience less dieback or mortality, acorn production and stump-sprouting should be similarly less affected. Following the 1988 drought, MNDNR reports indicated trees along logging and other roads often died from chestnut borer attack before other trees in the same stands. Increased exposure or wounds to residual trees, soil compaction, or other stress could increase potential impacts of the chestnut borer due to timber harvest.

Gypsy Moth
Finally, the gypsy moth was also included although not yet established in Minnesota. This pest has the potential to cause widespread changes to Minnesota's forests. Whether these changes occur or not is unlikely to be materially affected by the level of harvesting, and therefore consideration of this species is technically outside the scope of this study. However, the authors believe that this pest must be discussed because of its potential to cause widespread and very substantial impacts over much of Minnesota's forest lands irrespective of land use or tenure. Gypsy moth poses a threat to upland hardwood, aspen-birch and lowland hardwood forest types in Minnesota. The gypsy moth is not currently considered to be established in Minnesota. Isolated populations have appeared and have been eradicated via insecticide application. Information on the history and status of gypsy moth in Minnesota is presented in appendix A. The gypsy moth was originally introduced in 1869 to the northeastern United States and the range of gypsy moth infestation has subsequently expanded to the South and West. The gypsy moth is now well established in the Lower Peninsula of Michigan where almost 300,000 acres of wooded, residential area will be sprayed for

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gypsy moth suppression in 1992. Eastern Wisconsin will conduct an eradication effort on several thousand acres in 1992. A model of gypsy moth spatial dynamics has predicted natural expansion of the gypsy moth range into Minnesota between 2015 and 2025. This does not preclude the possibility of infestations arising from accidental introduction of egg masses or other life-stages. Impacts of gypsy moth in Minnesota are difficult to predict but are likely to be severe. Significant mortality and loss of growth and regeneration are likely, especially for preferred host species such as oak and aspen. Impacts on aesthetics and recreation may be severe, due to heavy defoliation and an abundance of larvae and frass.

Because gypsy moth is not established in Minnesota and because little data have been collected on impacts of gypsy moth in Lake States forests, it is difficult to predict impacts of increased harvest intensity. It is possible that increased harvest of upland hardwoods may reduce economic or biological impacts of gypsy moth, particularly if harvests are used to reduce preferred host species or susceptible/vulnerable trees. In general, younger trees are more able to tolerate defoliation than older trees, which also suggests that increased harvest intensity could decrease potential impact of gypsy moth. However, little data is available on population dynamics and impacts of gypsy moth in Lake States forests, particularly in aspen-birch stands.

Decay and Canker Organisms
Decay fungi cause the greatest losses in merchantable volumes in the upland hardwood species. There are several organisms responsible for decay (*Oxyporus populinus, Inonotus glomeratus, I. obliquus, Armillaria* sp.) and most of them infect trees through wounds (branch stubs, storm injuries, logging injuries). Use of silvicultural systems that retain a proportion of the stand following harvesting increase the likelihood that these diseases will spread. This is because residual trees are often wounded in the course of logging operations. Clearcutting avoids the problem of wounding residual crop trees, but is not always the preferred method. Upland hardwoods are often managed on an all-aged system where multiple entries are made into a stand on an 8- to 20-year cycle.

Canker fungi (fungi that cause localized areas of dead tissue) also increase volume losses, cause entry points for decay, and cause stem breakage. The most common canker fungi in upland hardwoods are *Nectria galligena* and *Eutypella parasitica*; these organisms invade trees through wounds. Nectria canker most commonly infects trees when they are 2 to 20 years old but may infect yellow birch throughout their lifetime. Most Nectria cankers are in the lower 10 feet of a tree where they can cause serious loss in timber quality. Eutypella canker most frequently kills trees less than 3 inches in diameter. On larger trees cankers reduce wood quality and increase the risk of wind breakage. If the incidence of Nectria canker is high in a stand, management

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should be directed to regenerating the site to less susceptible species (see mitigation measures).

Oak Wilt

Oak wilt is widespread throughout central and southeastern Minnesota (see map appendix B). Red, black and northern pin oaks are very susceptible to this killing disease; white oak is somewhat resistant and may not die when infected. This disease may be transmitted through root grafts or connected roots of healthy and diseased trees. This method of transmission forms the oak wilt *pockets* or circular, expanding areas of dying oaks. Overland spread may occur by sap-feeding beetles that may feed on fungal spore masses on infected trees then fly to fresh wounds on healthy trees to feed on sap flow. Oak wilt may be initiated during harvesting, timber stand improvements, pruning or any activity in the woods that wounds healthy residual oaks from mid-April through June (infected oaks must be present somewhere in the area to provide the initial inoculum).

Clearcutting may eliminate oak wilt pockets within clearcuts, but the disease can continue to move through root grafts in the clearcut and eventually reach healthy oaks surrounding the clearcut. Clearcutting could present a hazard if healthy oaks around the clearcuts or along skid trails that provide access to the clearcut are wounded from mid-April through June. There is also a hazard associated with removing infected red or black oak trees from the forest if fungal mats are present; the disease may be moved with the logs. Shelterwood harvest may be the harvest system of choice for oak. If this system is used and cutting occurs from mid-April through June, a short-term (<10 years) increase in the incidence of oak wilt can be expected as residual healthy oaks are likely to be wounded and infected during the shelterwood cut.

Background Factors and General Considerations

Upland hardwoods are susceptible to many pests that degrade the health of these forests. Some of these pests such as the two-lined chestnut borer and Armillaria root rot follow drought or defoliation by insects such as the forest tent caterpillar. Decay and canker organisms and sapstreak disease caused by the fungus *Ceratocystis coerulescens* are associated with wounds such as logging wounds or storm injuries. An increase in harvest will increase the need for monitoring of stressors that predispose upland hardwoods to pest outbreaks. Harvesting and regeneration systems that minimize wounding of residuals will be critical to maintaining healthy upland hardwoods. Regeneration through stump sprouts will require selection of sprouts originating from low stumps to minimize decay.

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3
METHODS FOR ASSESSMENT OF IMPACTS

3.1
Pests Potentially Affected By Changes in the Level of Timber Harvesting

As identified in the previous section, the risks of infestation will change for only a proportion of these pests as a consequence of timber harvesting and forest management activities. Therefore, the first stage of the analysis was to aggregate for subsequent analysis those pests whose incidence is likely to be affected, either positively and negatively, by timber harvesting and forest management activities.

3.1.1
Insects

Decisions on the importance of the pests to be included in this technical paper were based on a review of the literature, on interviews and surveys of state and federal pest management personnel and university forest entomologists in the Lake States, and on the expert opinion of the authors. Specific insect pests for each forest type group are presented in table 3.1.

Table 3.1. Forest type groups and associated important insect pests.

Forest Type Groups	Important Insect Pests (assessed in this review)	Species Affected	Others (not assessed)
Aspen-birch	forest tent caterpillar	Aspen	large aspen tortrix, bronze birch borer
Black spruce	spruce budworm	Black spruce	
Lowland conifers	spruce budworm	Balsam fir	larch sawfly
Lowland hardwoods			
Pines	white pine weevil, jack pine budworm, Ips pine engraver beetles	White pine Jack pine Red pine	white grubs, Saratoga spittlebug, pine tussock moth, pine sawflies
Spruce-fir	spruce budworm	White spruce Balsam fir	yellow-headed spruce sawfly
Upland hardwoods	two-lined chestnut borer	Oak sp.	pear thrips, basswood thrips, bud-mining complex, fall defoliator complex
	gypsy moth	many	

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These pest species were selected for analysis because of factors such as the frequency, duration and spatial extent of past outbreaks. In addition, the relative significance of impacts caused by past outbreaks were also considered. Of the species listed, some are of particular significance and have been separated under the heading "Important Insect Pests." Insect pests listed under this heading include those populations characterized by extensive spatial or temporal outbreaks and causing severe or widespread impact. In addition, insects causing severe but often localized impacts, or pests associated with drought or other specific conditions, were also included as was the gypsy moth for reasons discussed in the previous section.

Pests in the column labelled "others" were not assessed in this analysis as their populations are independent of the level of harvesting. They have been identified for completeness and to allow readers to consult appendix A for further information.

Detailed information on each pest species is presented in appendix A. The information includes life history of the pest, ecological and management-related factors contributing to pest outbreaks, impact of the pest, and strategies to manage or control the pest. The detailed information has been used to assess the susceptibility and vulnerability of the various forest types by age class. This information also provides the scientific basis for the range of possible mitigation measures presented in section 5.

3.1.2
Diseases

As with important insect pests, important forest diseases were also identified by covertype using information derived from the literature review and from reports by state and federal agencies responsible for disease assessment and control. Table 3.2 relates the important diseases to the respective covertypes.

Detailed information on each disease is presented in appendix B. The information includes a brief discussion of harvesting induced changes to relevant covertypes' susceptibility and vulnerability to the disease.

3.2
Assessment of Harvest Induced Changes in Susceptibility and Vulnerability by Forest Type Group

Forest type groups that are hosts to pests and diseases with the potential to be affected by the level of harvesting were identified in the previous section. This section draws on the summary information presented in section 2.4 and from the detailed information presented in appendixes A and B to detail the circumstances where harvesting alters susceptibility and vulnerability.

Table 3.2. Forest type groups and associated important diseases.

Forest Type	Important Diseases	Species Affected
Aspen-Birch	White trunk rot Hypoxylon canker *Armillaria* root rot	Aspen Aspen Aspen
Black Spruce	Eastern Dwarf Mistletoe	Black spruce
Lowland Conifers	*Armillaria* root rot Butt rot Trunk rot	Balsam fir Balsam fir Balsam fir
Lowland Hardwoods	Dutch elm disease Trunk rot	American elm Red maple
Pines	*Armillaria* root rot Red pine shoot blight *Scleroderris* canker *Diplodia* shoot blight and canker White pine blister rust Jack pine stem rusts	Red pine Red pine Red pine Red pine White pine Jack pine
Spruce-Fir	*Armillaria* root rot Butt rot Trunk rot Root rot	Balsam fir Balsam fir Balsam fir White spruce
Upland Hardwoods	Sapstreak Cankers Decay Canker Oak wilt *Armillaria* root rot	Sugar maple Sugar maple Sugar maple Yellow birch Oak sp. Oak sp.

Typically, these changes involve differences between age classes and the effects of multiple entry harvesting systems. The information has been broken down by covertype group by pest and is summarized in table 3.3. This analysis depicts changes that are likely at the statewide level of resolution. As discussed, it does not take into account the myriad of site specific factors that can alter vulnerability and susceptibility when assessed at a specific site level of resolution.

3.3
Assessment of Changed Susceptibility and Vulnerability

The impacts of increasing levels of timber harvesting and forest management activities on forest health were assessed by analyzing data derived from the initial and second harvesting scenarios (Jaakko Pöyry Consulting, Inc. 1991b, 1992a). The output for each scenario was summarized by forest type and potentially sensitive tree species. The data attributes used included: changes

in the age class distribution for each forest covertype grouping; and the incidence of multiple entry harvesting systems. The summarized results provided the basis for the analysis of impacts over the planning horizon.

Table 3.3. Assessment of harvest induced changes in susceptibility and vulnerability by forest type group.

Forest Type Groups	Insect or Disease Pests Likely to be Affected by Harvesting	Factors Affected by Harvesting		
		Age Class (years)		
		More Susceptible/ Vulnerable	Less Susceptible/ Vulnerable	Multiple Entry
Aspen-birch	Forest tent caterpillar	older	younger	NA
	White trunk rot	>40-50	<40	NA
	Armillaria root rot	younger[a]		NA
Black spruce	Root and butt rot	>60	<40	NA
	Eastern dwarf mistletoe[b]			
Lowland conifers (especially balsam fir)	Spruce budworm	>40	younger	NA
	Armillaria root rot	>50	younger	NA
	Butt rot	>50	younger	NA
	Trunk rot	mature-older		NA
Lowland hardwoods	Trunk rot	NA	NA	increased susceptibility
Pines	White pine weevil	<40	>40	NA
	Jack pine budworm	older	younger	NA
	Ips pine engraver beetle[c]			potential to increase susceptibility
	Armillaria root rot[c]			NA
	Red pine shoot blight[c]			NA
	Scleroderris canker[c]	<20	>20	NA
	Diplodia shoot blight and canker[c]	NA	NA	NA
	White pine blister rust	<10	older	NA
	Jack pine stem rust[c]			NA
Spruce fir (especially balsam fir)	Spruce budworm	>40	younger	NA
	Armillaria root rot	>50-60	younger	NA
	Butt rot	>50-60	younger	NA
	Trunk rot	>50-60	younger	NA
	Root rot	>50-60	younger	NA
Upland hardwoods	Two-lined chestnut borer	older	younger	increased susceptibility
	Sapstreak	NA	NA	increased susceptibility
	Cankers	<20	older	increased susceptibility
	Decay	NA	NA	increased susceptibility
	Oak wilt	NA	NA	increased susceptibility
	Armillaria root rot	NA	NA	increased susceptibility

[a]Potential for increased vulnerability due to repeated short rotation.
[b]Incidence depends on how harvesting is done.
[c]Independent of level of harvesting—incidence related to postharvesting treatment.

3.3.1
Assumptions

These assessments required certain assumptions regarding the degree of compliance with insect and disease control guidelines that is likely to occur following projected timber harvesting operations. Of the guidelines presented in section 2.3.2, those of particular interest in developing the assessments of changed vulnerability relate to regeneration of species and covertypes that have special requirements for site selection.

The following describes the assumptions made in relation to the management, regeneration and harvesting operations that are undertaken. These assumptions represent a simplification of real world management and there will obviously be localized exceptions if practices were assessed at a stand level of detail. However, these simplifications do not add substantially to the level of uncertainty associated with the analysis because:

- of the statewide level of resolution of these analyses; and
- the fact that the level of certainty attained in these analyses is defined more by the limited state of knowledge regarding pest/host interactions than by any assumptions made regarding use of management practices.

Management
An assumption that guidelines will always be used in the course of silvicultural treatments and in plantation establishment is reasonable because most of these activities will occur on ownerships with comparatively sophisticated management including: MNDNR, counties, USDA Forest Service, forest industry and motivated private individuals. Owners undertaking these types of management activities without direct access to such advice would have indirect access through some form of technical assistance, such as that provided to NIPF owners by forest extension services.

Regeneration
The analysis assumes that where sites are harvested and artificial regeneration is required, the sites will be returned to the species that previously occupied the site. Therefore, there are assumed to be no changes to vulnerability due to poor site selection.

Harvesting
Harvesting systems are assumed to be those currently in use in Minnesota as described in the Harvesting Systems background paper (Jaakko Pöyry 1992b). Typically, tree length skidding systems are used in Minnesota for thinning and selective harvesting operations. Tree length skidding causes comparatively high levels of damage to residual stems. By assuming that

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these systems are used, there is an implicit assumption that there will be typically high levels of damage to retained stems each time a stand is either thinned or selectively harvested.

As a consequence of these assumptions, the focus of the impact assessment moves from the site, species selection and impacts related to silvical techniques to changes to fundamental aspects of the state's forests. These changes are to the age class distributions by covertype; and to the incidence of multiple-entry harvesting operations.

3.3.2
Changes in Age Class Distribution

Assessment of Changes in Age Class Distribution

Figure 3.1 illustrates a change in the age class distribution for a forest type group at the start and end of the planning period. The initial distribution was weighted towards older age classes. In contrast, the final distribution is weighted towards the younger age classes. The forest health consequences of this change would vary depending on the forest type group. One that becomes increasingly susceptible/vulnerable to insect and disease attack with increasing age would be assessed as being positively impacted by the change shown in figure 3.1. However, for those forest type groups that are more susceptible as younger stands, the change shown in figure 3.1 would be considered a negative impact as more area of susceptible/vulnerable forest would have been created.

Projected changes in the area of specific forest types by age class were calculated for each scenario. Because the significance threshold was set at a low level (10 percent change for susceptible/vulnerable area), the step of identifying *all* changes was passed over. Instead only those impacts above the threshold level were recorded. The assessment of changed susceptibility/ vulnerability by age class (table 3.3) was used to identify those forest covertype groups which were potentially impacted by changes of greater than 10 percent in their age class distribution.

3.3.3
Incidence of Multiple Harvest Entries

Output of the final harvest scenario was used to estimate the incidence of multiple harvest entries. These were projected to occur on plots that were thinned and on plots managed under uneven-aged management. The area thinned varied among the scenarios, from over 350,000 acres in the base scenario; to about 600,000 acres in the medium scenario; and to about 1,000,000 acres in the high scenario (figure 3.2). This corresponds to a doubling over base levels for the medium scenario and a tripling for the high scenario.
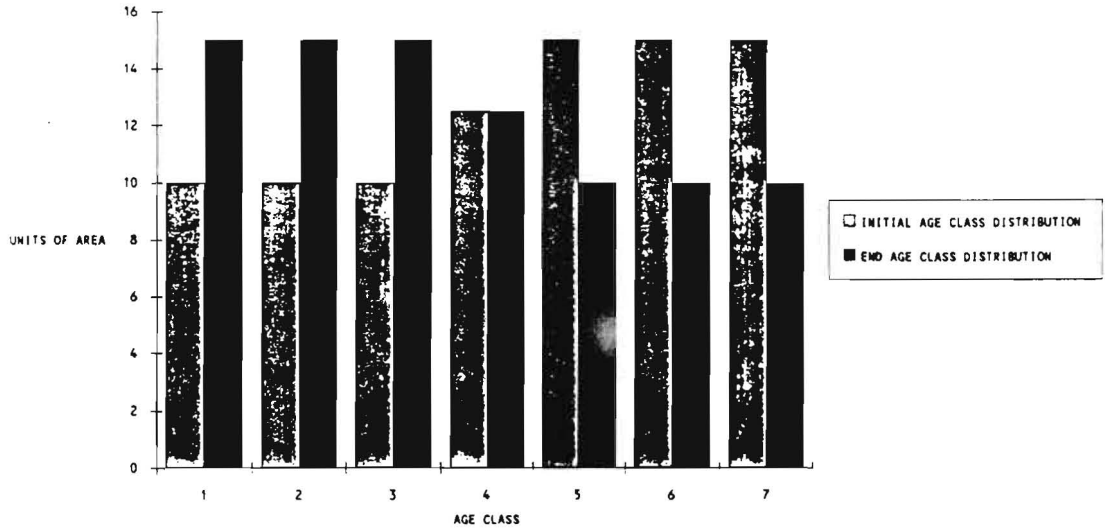
Figure 3.1. Example of a change in age class distribution for a forest type group at the start of the planning period and at the end of the planning period.
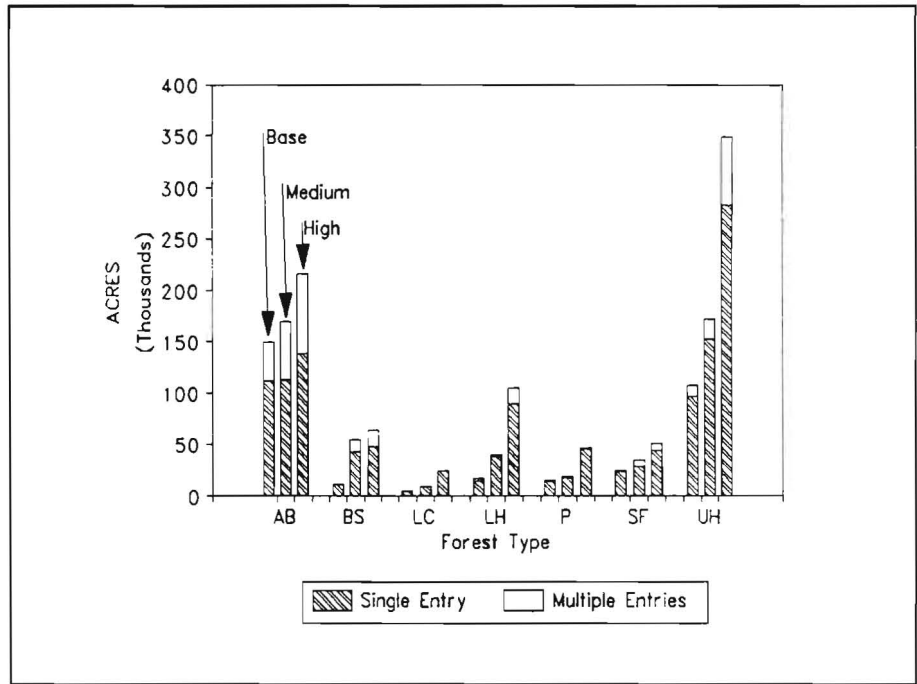
Figure 3.2. Area of each of seven forest type groups[a] affected by one or more stand entries related to thinning or other types of uneven-aged management under three harvest levels. Final model runs 1990–2040.

[a]AB = Aspen-birch, BS = Black spruce, LH = Lowland hardwoods, P = Red, white and jack pine, WP = White pine, SF = Spruce-fir, UH = Upland hardwoods.

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4
SIGNIFICANT IMPACTS

4.1
Significance Criteria

4.1.1
Background

Impacts identified in the course of this study will vary in their significance and, therefore, in the need to develop a specific mitigation response. This is a critical stage of the study process, as these tests of significance will ultimately define the scope of policy recommendations developed by the GEIS.

Identification of an impact as being significant does not automatically prescribe a specific mitigation response. The significance criteria have been developed to be inclusive rather than exclusive. Their purpose is to identify the issues and circumstances where policy initiatives will be required. The range of possible policy responses, the factors used to choose between them, and the implications of selecting a particular response are all evaluated by subsequent criteria.

For each significance criterion developed, several background factors were used to determine levels or thresholds when impacts are likely to be considered significant. They include:

- severity and spatial extent of impact;
- certainty of impacts;
- duration of impact (irreversibility);
- consideration of existing guidelines and standards; and
- biological and economic implications.

The first factor identifies the likely extent and severity of an impact. Impact extent varies considerably ranging from very localized site specific impacts to those impacting a watershed, physiographic region, soil type, covertype, ecoregion or the entire state. The second factor identifies the degree of certainty that a predicted impact will occur. The key factors influencing certainty are identified for each criterion. The third factor incorporates the anticipated duration of the impact, and whether or not it is reversible. Duration is defined as very short-term—less than 2 years; short-term—2 to 10 years; medium-term—10 to 50 years; long-term—greater than 50 years; and irreversible. The fourth factor incorporates those existing standards and guidelines that are applicable to the respective issue areas. The fifth factor identifies the key biological and economic implications of the impact. These are particularly important in those circumstances where impacts are indirect.

For example, loss of mast (e.g., acorns) producing trees is the impact criterion and what makes this loss significant is its effect on populations of animals dependent on these trees for food.

4.1.2
Forest Health Significance Criterion

Criterion 6. Forest Health—change in susceptibility or vulnerability.

> An impact is considered significant if projected changes to the forest and activities undertaken lead directly or indirectly to changed susceptibility (risk of an outbreak/infection) or vulnerability (damage if an outbreak occurs) to more than 10 percent by area by covertype.

Severity and/or extent. The criterion is intended to identify changes that will affect the susceptibility and vulnerability of Minnesota's forests to infection and outbreak of pests and disease. Susceptibility refers to the risk that a pest or disease will build to outbreak or unusually high levels in a stand. Vulnerability describes the likelihood that serious damage will occur if an outbreak occurs. Many abiotic and biotic factors interact to determine stand susceptibility and vulnerability.

The severity and extent of changes will be assessed by interpreting changes in age class structure and silvicultural systems applied, particularly those resulting in uneven-age management. Emphasis will be on identifying the circumstances likely to change the proportion of susceptible/vulnerable age classes, and the circumstances that require multiple entry harvesting operations. The 10 percent change in susceptible or vulnerable area by covertype has been selected as the minimum threshold determining when change is significant. This is because 10 percent is likely to be the minimum change needed to substantially affect susceptibility or vulnerability to most forest pests, and is the minimum level that is detectable above naturally occurring variation.

Generally, the potential for pest outbreaks and damage is related to stand vigor, tree and ecosystem resilience, and also to the maintenance of biological controls to prevent the buildup of damaging insect and disease populations. In many cases, younger stands with more vigorously growing trees are less susceptible to population build-up or are better able to tolerate or recover from pest damage. However, this varies as some pests preferentially attack young trees. Susceptibility and vulnerability may also be associated with thinning or multiple entries into stands. Damage to residual stems may reduce tree vigor and can provide an entry point for disease and insects to attack. Debris left in thinned or harvested stands can also provide conditions that favor some pests.

Certainty of impact. Many variables influence the likelihood of a change in susceptibility and vulnerability. These include: forest age class structure, stand vigor, silvicultural systems, harvesting systems, development of extensive areas of single species plantations, species diversity at the stand and landscape levels, and adherence to stand sanitation measures.

Duration of impact (irreversibility). The duration of impact can vary from short- to long-term depending on: pest and host species, site conditions and biotic and abiotic variables. For example, a single defoliation may reduce productivity for a season but have no lasting effects. Other pests, such as oak wilt, that kill the host will likely have a lasting impact on the stand extending into the long-term.

Biological implications. Outbreaks of insects and disease typically impact older or less vigorous components of the stand, although regeneration may also be affected. In addition, certain species appear more susceptible. Therefore, age class and species composition of forests could be significantly affected by pest and disease infestations. In turn, such changes affect habitat suitability, improving conditions for some species, and reducing habitat for others. Some forest pests, particularly insects, may be used as food by other animals. Large pest outbreaks may predispose stands to subsequent increased fire hazard.

Existing guidelines and standards. The Minnesota DNR has developed guidelines for silvicultural management of major insect and disease pests in Minnesota forest types. These provide general recommendations, but it must be recognized that appropriate management and control practices will depend on site, environmental conditions and economic conditions specific to each situation.

Economic implications. Insects and disease are the major factors causing reduced wood production. Widespread occurrence of tree death and defoliation caused by outbreaks of insects and diseases have the potential to adversely affect aesthetic values and therefore, recreation and tourism industries.

4.1.3
Background to Impact Assessments

All timber harvesting and forest management activities affect forest health; all have impacts. Those impacts range from nearly none (where the management activity is minimal) to very significant (where major changes are brought about in the forest). That continuum of impacts is impossible to treat in any quantitative sense so a threshold must be established to aid in communication. Impacts that are greater than that threshold merit attention;

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impacts below the threshold are not large enough to justify further consideration.

General Health Impacts. Some impacts on forest health associated with an increase in timber harvesting do not directly relate to a particular pest or do not meet criterion 6, change in area of a covertype of more than 10 percent. Some of these impacts are associated directly with the harvesting operation and some are associated with regeneration and management of the harvested species. These were discussed for each forest type in section 2.4, and provide background for more detailed guidelines useful for field management.

4.2
Comparison of Initial and Second Run Harvest Scenarios

There were two sets of harvesting scenarios produced as part of the GEIS process. Each set had a base, medium and high scenario that met the specified levels of timber demand. The runs differed in the assumptions used to specify the proportion of timberlands that were available for harvest, how harvest was to be conducted and key aspects of stand management. These aspects include minimum age before harvesting could occur and longer rotation objectives, i.e., extended rotation forest, and the provision for retaining existing old growth and older forest that might replace the old growth. The Maintaining Productivity and Forest Resource Base technical paper (Jaakko Pöyry Consulting, Inc. 1992a) fully describes both sets of scenarios including the assumptions used, timber supply implications and the consequences for the state's timberlands in terms of changes to key indicators such as species composition and age class distribution. These changes will have significant consequences for forest health. Comparison of the initial with second run scenarios provides the means to examine some of the forest health implications of decisions to extend rotations, reserve old growth and set aside areas from harvesting.

The initial scenarios planned harvest levels that were relatively free of constraints; they emphasized designated harvest levels and did not include measures to mitigate some of the potential impacts of that management strategy on other values from the forest. Harvest levels achieved under the second scenarios included mitigation measures as discussed above. Though these measures had a variety of objectives, their ultimate result was a shift toward longer rotations and retention of older stands, leading to a difference in the resulting age-class distribution of the forest types.

The effect of these differences can be illustrated by data for the aspen-birch forest type group, although the effect was present to some degree in all of the forest type groups that were evaluated. At the base level of the initial

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scenario, about 5.5 million acres of aspen were in the 0 to 40 age class at the end of the planning horizon, and almost 90,000 acres were in the >70 age class (figure 4.1). At the high level of that scenario, nearly 6 million acres were in the youngest age class and only about 60,000 acres in the oldest class (figure 4.1). These changes also indicate the consequences of presenting such data using a logarithmic scale, as in figure 4.1. Although this scale allows data that are quite different in magnitude to be displayed on the same figure, small differences at the high end of the scale (e.g., 0 to 40 age class) represent many more acres than do larger changes at the lower end of the scale (e.g., > 70 age class). .

In contrast to the results of the initial harvesting scenarios, at the base level of the second scenarios only about 3.8 million acres of the aspen-birch forest type group were in the 0 to 40 age class at the end of the planning horizon, and almost 800,000 acres were in the >70 age class (figure 4.2). Even at the high level of that scenario, less than 5.5 million acres of aspen-birch forest type group were in the youngest age class and about 180,000 acres were in the oldest class at the end of the planning horizon (figure 4.2). Because older stands are generally less able to resist stress, and are both more susceptible to insects and disease and more vulnerable to injury, these results have important implications for forest health. Nearly ten times more area is occupied by old stands under the base level of the second scenarios compared to the base level of the initial scenarios, hence a greatly increased forest area is at risk for forest health problems. Results similar to those for the aspen-birch forest type group occurred for all forest type groups; a shift to older age classes under the three harvest levels of the second scenarios compared to the initial scenarios. **The initial scenarios will not be further discussed, and the analysis of harvesting impacts will concentrate on the results from the second scenarios, which are considered to represent a more realistic management scenario.**

4.3
Assessment of Significant Impacts by Forest Type Group

This section interprets significant impacts on forest health that are projected to occur under the base, medium and high levels of harvesting described earlier. These impacts are summarized in table 4.1. Criteria used to assess impacts included severity or extent, certainty, duration or irreversibility, and implications of impacts.
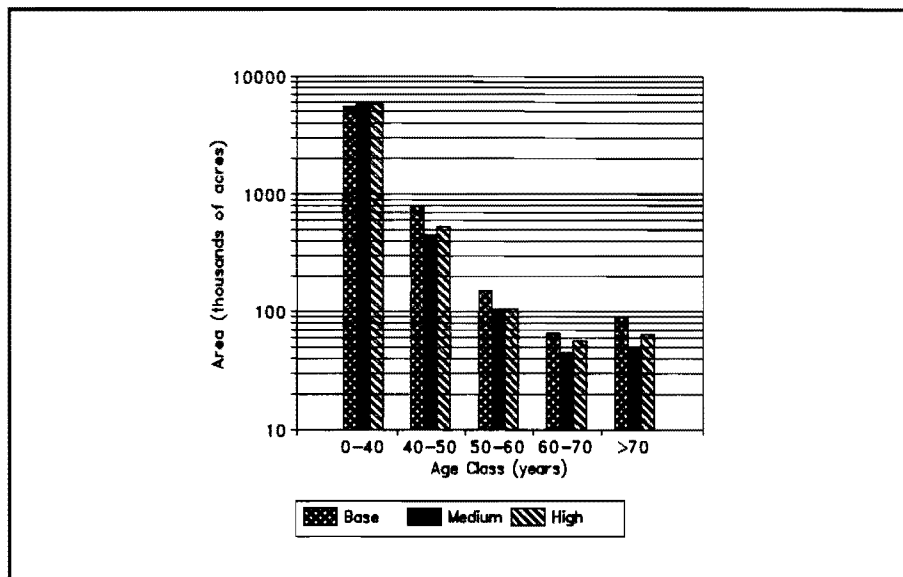
Figure 4.1. Area of the aspen-birch forest type group by age class resulting from three timber harvesting levels from the initial scenarios.
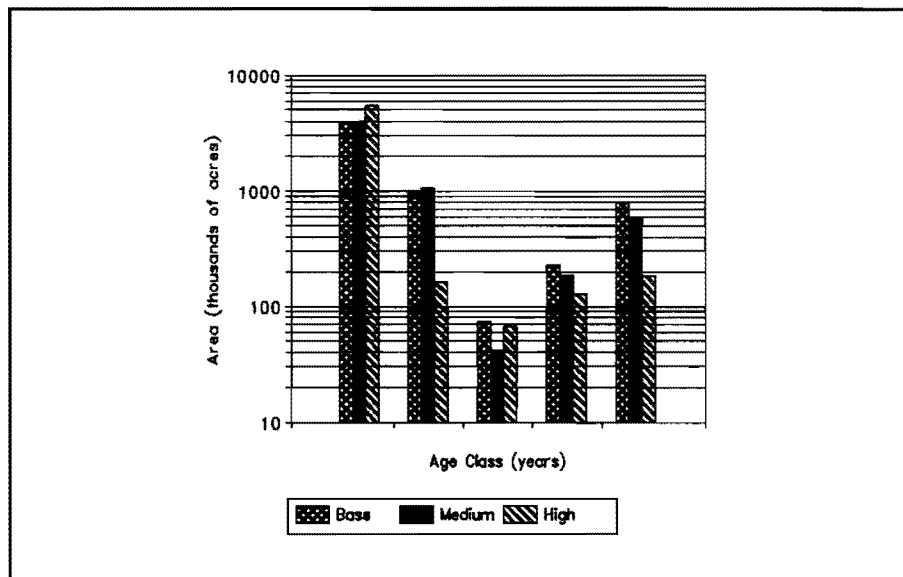
Figure 4.2. Area of the aspen-birch forest type group by age class resulting from three timber harvesting levels from the second scenarios.

Table 4.1. Assessment of significant impacts of increased levels of timber harvest, in comparison with base conditions, on major insect pests and diseases of Minnesota forests. Assessment of severity/extent, certainty, and duration/irreversibility was based on a scale of 1 to 3. In this scale, 1 indicated low severity or extent, low certainty of impact, or short duration or highly reversible impact. Conversely, 3 indicated very severe or widespread impact, highly certain occurrence of impacts, or long-lasting or irreversible impacts. Positive (+) or negative (-) implications of impacts on forest health are indicated.

Forest Type[a]	Insect/ Disease	Harvest Scenario	Severity/ Extent[c]	Certainty of Prediction[c]	Duration/ Irreversibility[c]	Implications[c] (+/-)
AB	Forest Tent Caterpillar	Medium	NC[b]	2		
		High	2	3	2	+
	White Trunk Rot	Medium	NC	2		
		High	2	3	2	+
	Hypoxylon Canker	Medium	NC	2		
		High	1	2	1	+
	Armillaria Root Rot	Medium	NC	2		
		High	1	2	1	-
BS	Dwarf Mistletoe	Medium	2	3	1	+
		High	2	3	1	+
P	White Pine Weevil	Medium	NC	2		
		High	3	3	3	-
	White Pine Blister Rust	Medium	NC	2		
		High	2	2	2	-
	Jack Pine Budworm	Medium	NC	2		
		High	1	3	2	+
	Diplodia	Medium	NC	2		
		High	1	3	2	-
	Scleroderris	Medium	NC	2		
		High	1	3	2	-
	Ips Bark Beetles	Medium	NC	2		
		High	1	2	2	+
SF	Spruce Budworm	Medium	2	3	2	+
		High	1	3	2	+
	Root, Butt, Trunk Rots	Medium	2	2	3	+
		High	2	2	3	+
UH	Two-lined Chestnut Borer	Medium	2	2	2	+
		High	1	2	2	+
	Cankers/ Decay	Medium	1	2	2	-
		High	2	2	2	-
	Oak Wilt	Medium	1	1	2	-
		High	2	1	2	-

[a] AB=Aspen-Birch, BS=Black Spruce, LH=Lowland Hardwoods, P=Red, White and Jack Pine, WP=White Pine, SF=Spruce-Fir, UH=Upland Hardwoods.
[b] NC= Change in area of susceptible/vulnerable age classes <10 percent.
[c] A discussion of these factors follows the significance criterion in section 4.1.2.

As discussed in section 3.3, certain assumptions were made as part of the analysis. In particular, it was assumed that the MNDNR pest management guidelines and other guidelines would be followed by all ownerships. If the guidelines are not followed, impacts of harvesting on the health of Minnesota's forests could be more severe. This is because the guidelines are intended to prevent pests and diseases from becoming established by avoiding the creation of conditions that are suitable for pests. If these guidelines are not followed then it is likely that pests will become established. Planting of white pine on sites with a high risk of while pine blister rust infection is a good example. More specific information concerning impacts is provided in the text following the table.

Increased use of pest management guidelines, especially by those ownerships who do not currently have access to this information, would be moderately effective. The effectiveness of the guidelines would be limited due to problems caused by the lack of professional judgement that may be required. It is also only moderately feasible because of the difficulties of finding a way to disseminate the information. The duration of the mitigation would be short- to long-term.

4.3.1
Aspen-Birch Forest Type Group

The area of the aspen-birch forest type group more than 40 years old would change less than 10 percent at the medium harvest level, and would decrease by more than 10 percent under the high harvesting levels (figure 4.2). This change will alter the susceptibility and vulnerability of this forest type group to outbreaks of specific insect and disease pests.

The reduction in the proportion of stands in the older age classes that are projected to occur following increased levels of harvesting may reduce vulnerability to damage from the forest tent caterpillar. Consequently, mortality and volume loss associated with defoliation may decrease, although quantitative data to support this judgement are lacking. Therefore, this is a significant positive impact. Other impacts, including effects of forest tent caterpillar on aesthetic and recreational values, are not likely to change.

The incidence and severity of decay due to white trunk rot should be reduced as the older, more decayed stands are cut under the high harvest level. Aspen less than 40 years old will not be free from decay but the percent of wood decayed will be less in the younger stands. To maximize the possibility of a positive impact, management must be followed that minimizes decay. Well-stocked aspen stands on average sites grown with protection from fire on a 40- to 50-year rotation will not be greatly affected by decay.

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Under projected increases in harvest level, Hypoxylon canker should decrease if management guidelines for its control are followed (see mitigation measures). Good harvesting practices should ensure well-stocked stands, reducing infection.

Under projected increases in harvest, Armillaria may increase. Root rot incidence can increase as a function of stand age, but if soil compaction and rutting occur during the harvest, root injury may occur and increase the incidence of *Armillaria*.

4.3.2
Black Spruce Forest Type Group

The area of black spruce forest type group less than 40 years old would increase by more than 10 percent while the area over 60 years old would decrease by more than 10 percent under the medium and high harvest levels in the year 2040 (figure 4.3).
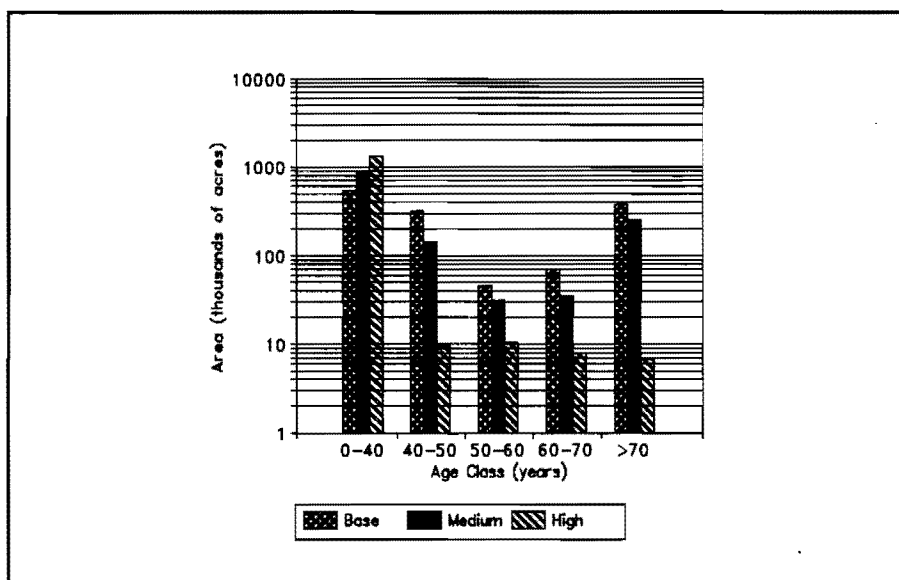
Figure 4.3. Area of the black spruce forest type group by age class resulting from three timber harvesting scenarios.

The projected increase in the area of black spruce forest type group harvested under the higher cutting scenarios should lead to a short-term decrease in the incidence of eastern dwarf mistletoe if the clearcuts include areas already infected with mistletoe. Therefore, this is a significant positive impact.

The greater than 10 percent reduction in the area of stands older than 60 years that is projected to occur under the medium and high levels will reduce

the incidence of root and butt rot caused by *Inonotus tomentosus*. Therefore, this is a significant positive impact.

4.3.3
Lowland Conifers Forest Type Group

The area of lowland conifers less than 40 years old would increase by more than 10 percent under the medium and high levels of harvest. Under the high harvest level, the area of lowland conifers more than 60 years old would decrease by more than 10 percent (figure 4.4). Impacts on balsam fir stands are as discussed under spruce-fir below. For the remaining species, whether significant changes in harvest intensity are likely to change susceptibility or vulnerability of lowland conifer stands to insect and disease pests is unknown.
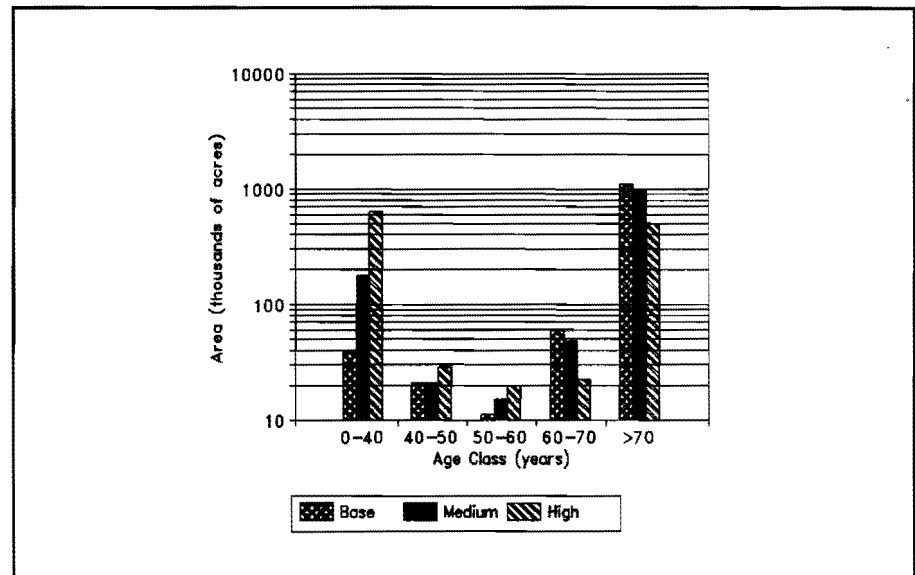
Figure 4.4. Area of the lowland conifer forest type group by age class resulting from three timber harvesting levels.

4.3.4
Lowland Hardwoods Forest Type Group

The area of lowland hardwoods fores type group less than 40 years old would increase by more than 10 percent under the medium and high harvest levels. Under the medium and high harvest levels, the area in the more than 60-year-old age class would decrease by more than 10 percent (figure 4.5). There are relatively few major pests that are likely to be affected by changing the level of harvest in lowland hardwood types.

Figure 4.5. Area of the lowland hardwood forest type group by age class resulting from three timber harvesting scenarios.

4.3.5
Pine Forest Type Group

Under the high harvest levels, the area of pine forest type group less than 40 years old would increase by more than 10 percent; while the area in the >60-year-old age class would decrease by more than 10 percent (figure 4.6). Changes would be near or less than 10 percent under the medium harvest level. The following discusses the implications of these changes for each pine species.

Because under the high level of harvesting the acreage of mature and overmature pine forest type group decreases by more than 10 percent, the extent of jack pine budworm outbreaks and the damage associated with severe feeding are likely to decrease, reducing the levels of damage caused by this pest. This is a significant positive impact.

Incidence of *Diplodia* shoot blight and canker and *Scleroderris* canker on young (<40 years old) red pine may increase if the areas replanted to red pine are not carefully chosen. Both of these pests are not major problems on older red pine so the predicted decrease in area of pine more than 40 years old in the high harvest level should not have a significant effect on disease incidence in older red pine. There is a potential for an increase in diseases such as needlecasts and gall rust as nursery seedlings are planted to replace the trees that have been harvested. Lophodermium needlecast on red pine

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and gall rust of jack pine are two diseases that can be introduced into the field on infected nursery stock.

A decrease in area of older pine forest type group may reduce the amount of pine that is less vigorous and less able to resist Ips beetles following damage by wind, lightning, flooding, defoliation or pathogens. Incidence of Ips may therefore decrease under the high levels of harvesting.
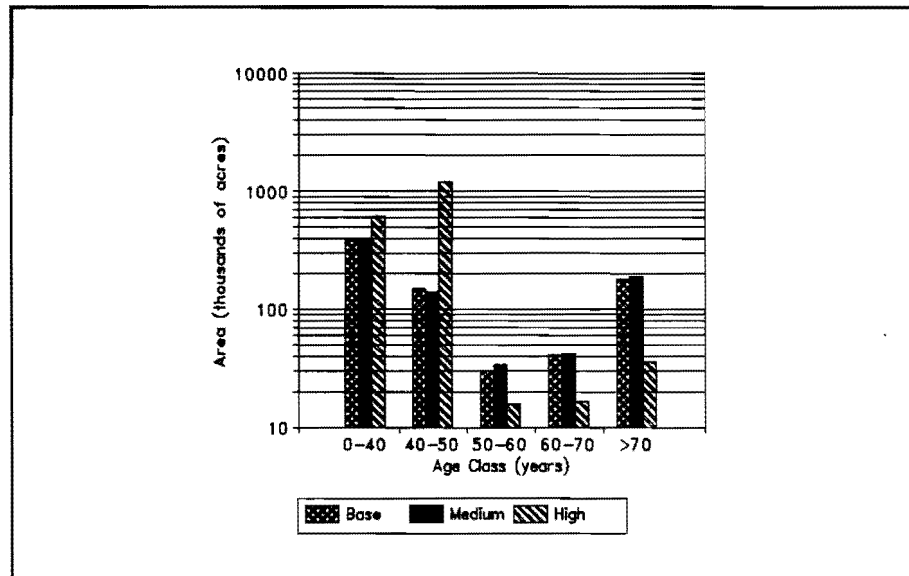
Figure 4.6. Area of the pine forest type group by age class resulting from three harvesting scenarios.

At the higher harvest levels, harvested white pine stands are assumed to be replaced by younger stands that are more susceptible and vulnerable to white pine weevil (figure 4.7). Therefore, this is a significant adverse impact. The increase in younger white pine could increase the incidence of white pine blister rust, especially if white pine is regenerated in northern Minnesota. Therefore, this is a significant adverse impact.

4.3.6
Spruce-Fir Forest Type Group

The area of spruce-fir forest type group less than 40 years old would increase by more than 10 percent under the medium and high harvest levels, and the area more than 40 years old would decrease by more than 10 percent at those levels (figure 4.8).

Under increased harvesting levels, the overall reduction in tree age within

this forest type group will reduce vulnerability and susceptibility of stands to budworm damage. Younger trees produce fewer staminate cones and are less likely to experience population outbreaks. Younger trees are also generally more tolerant of defoliation than mature or overmature trees. Probability of wildfire should decrease since mortality, breakage, and windthrow that follow budworm outbreaks will decrease. This will prevent the major fuel buildup that can lead to wildfire. Therefore, this is a significant positive impact.
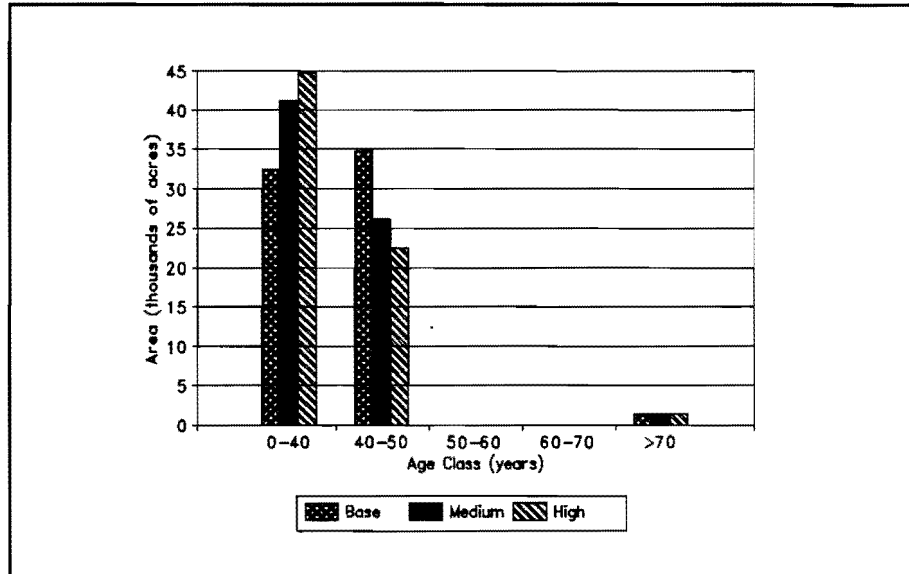
Figure 4.7. Area of the white pine forest type group by age class resulting from three timber harvesting scenarios.

The reduction in area of older spruce-fir forest type group will lead to a reduction in the level of susceptibility and vulnerability of these species to trunk, root and butt rots. This is a significant positive impact.

4.3.7
Upland Hardwoods Forest Type Group

The area of upland hardwoods forest type group less than 40 years old would increase under the medium and high harvest levels and the area more than 60 years old would decrease by more than 10 percent under both harvest levels (figure 4.9).

Under the higher levels of harvesting intensity, the area of younger trees will increase. Younger trees are generally more vigorously growing and have more starch reserves than older trees. They are therefore less affected by

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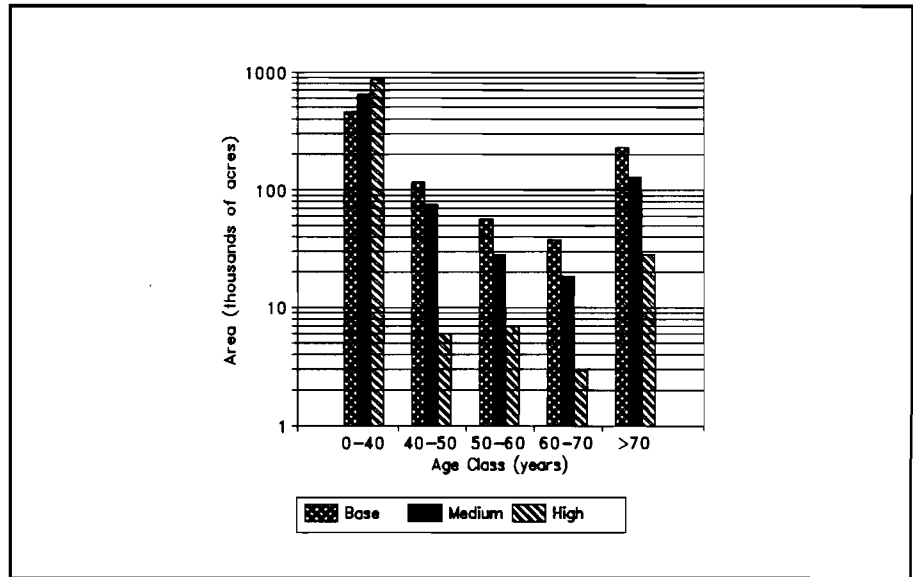
Figure 4.8. Area of the spruce-fir forest type group by age class resulting from three timber harvesting scenarios.

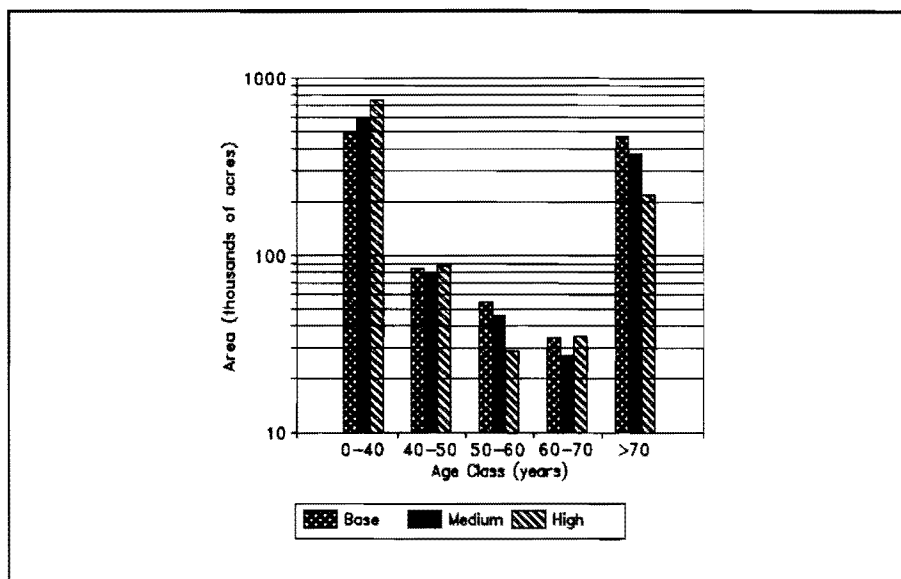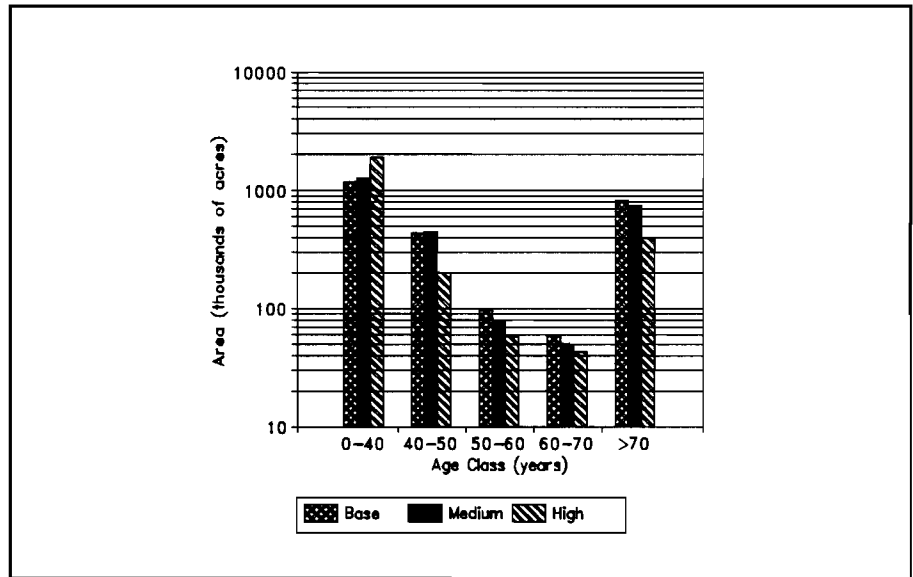**Figure 4.9.** Area of upland hardwoods forest type group by age class resulting from three timber harvesting scenarios.

drought and other environmental stress and presumably less susceptible to severe damage by two-lined chestnut borer. Therefore, a reduction in the area of older trees could result in a decreased impact of chestnut borer.

Clearcutting stands of upland hardwoods forest type group should reduce the incidence of decay in the mid-term (10 to 50 years) and cankers in the short-

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term (< 10 years) as decayed and cankered trees are removed from the stand. However, selection and shelterwood cuts are often preferred methods of regenerating stands of upland hardwood forest type groups. If some type of multiple entry harvest is chosen, the chances of wounding residual trees increases; the incidence of decay and cankers is also likely to increase. Thinning and other stand entries are projected to increase substantially in stands of upland hardwood forest type groups under both the medium and high harvest levels (figure 3.2). Hence the overall impact of increased harvesting is a likely increase in decays and cankers.

Under the proposed increase in timber harvest, a medium term (10 to 50 years) decrease in the incidence of oak wilt is expected if clearcutting is the method of harvest. Clearcutting would eliminate oak wilt pockets within the clearcuts. Multiple stand entries may tend to injure oak, and make them more susceptible to infection. Given that multiple entry harvest will predominate, the amount of oak wilt is therefore projected to increase with increase in harvesting (with high uncertainty of prediction).

5
POSSIBLE MITIGATION MEASURES TO ADDRESS SIGNIFICANT IMPACTS

5.1
Mitigation Alternatives Criteria

These criteria will identify mitigation actions with the potential to address the significant impacts previously identified. The purpose behind this stage of the process is to identify mitigation actions which are effective and practical in a physical context, as well as the political, financial, and administrative environments in Minnesota.

Input from the technical experts, Advisory Committee, and the EQB are reflected in the criteria as presented. Unlike the significance criteria, the criteria developed to identify potential mitigation alternatives will be applied uniformly across all issue areas documented in the FSD (MEQB 1990).

Major considerations used in the development of criteria to identify mitigation alternatives include:

- financial considerations;
- administrative considerations;
- certainty of effectiveness; and
- social implications.

> A mitigation alternative to address identified significant impacts will be considered if the mitigation is physically and biologically *feasible to implement*[1] in Minnesota taking into account the:
> * administrative requirements to implement and oversee policy changes;
> * the financial requirements to undertake the action; and
> * social considerations (ability to organize support and effect implementation).

The mitigation action must also be supported by some degree of certainty regarding its effectiveness, both in terms of the relative extent of mitigating the impact and its duration at maintaining the mitigative effectiveness.

In practice, the verbal and written input from the Advisory Committee on the potential mitigation strategies led to acceptance, rejection and/or refinement of the potential strategies. These results were then approved by the EQB and comprise the strategies considered and evaluated in detail.

5.2
Mitigation and Land Ownership

Many of the mitigation alternatives that are presented are well-accepted pest management recommendations. Public land management agencies are more likely to implement appropriate mitigation measures; mitigation on nonindustrial private forest land will continue to be a challenge. Therefore implementation of these alternatives may be difficult given the large percent of private timberland owners. Farmers and miscellaneous private owners control 43.5 percent of the nearly 15 million acres of timberland in Minnesota (figure 5.1) (draft of *Minnesota Resource Statistics 1990* [Miles and Chen n.d.]). If an increase in harvesting occurs, implementation of the mitigation alternatives becomes critical to maintaining healthy forests. This will require more contacts with private landowners to inform them of forest management practices, including pest management alternatives.

5.3
Mitigation Strategies

There are two levels at which strategies that mitigate the effects of timber harvesting on forest health can be considered. At one important level, mitigation can be considered by forest type and individual pest. This is a

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[1]*Feasible* implies that the mitigation action can realistically be implemented and addresses the impact being considered.
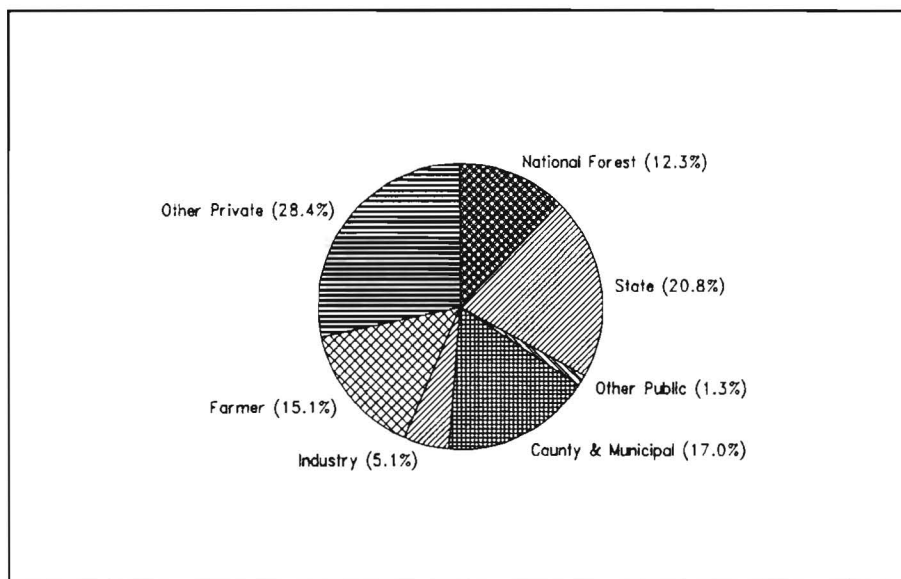
Figure 5.1. Distribution of forest land by ownership in Minnesota, 1990.

traditional and powerful approach, and has led to the development of culturally-based management guidelines such as those produced by the MNDNR (MNDNR 1990). This technical paper does not consider mitigation strategies at this level except to recommend strategies to increase application of these guidelines.

Mitigation strategies can also be considered and evaluated at a broader level of generalization, and one that is more appropriate for the level of resolution of a statewide GEIS. This paper focuses on strategies to improve planning and management to enable the major forest owners to prevent adverse forest health impacts, monitor pest populations, plan appropriate response measures and lastly to implement the guidelines discussed above.

5.3.1
Strategies to Prevent Impacts

Major timberland ownerships should monitor, and if necessary manipulate, the proportion of forest type groups that are maintained in susceptible and vulnerable age classes.

Effectiveness
Maintenance of productive forests and avoidance of damaging outbreaks can reduce the mortality and losses of production caused by pests and diseases. The major ownerships should monitor changes in age class distributions using the procedures suggested by this study. By using such procedures, trends towards increases in susceptible or vulnerable age classes can be detected.

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Early detection of these trends will allow time to plan ameliorative measures for particular species/forest type groups such as those outlined in the guidelines described previously. In addition, where these changes are inconsistent with management objectives and older age classes are involved, early detection would allow forest owners to re-order the sequence of harvesting to focus on these age classes and therefore reverse these trends. This would allow owners to either avoid or capture mortality (harvest trees before they become unusable) rather than losing potentially valuable timber.

This mitigation would also allow the larger public ownerships to monitor changes in age class distributions that reflect deliberate policy initiatives. For example, the extended rotation management being applied to some covertypes is aimed at increasing the proportion of mature and older stands.

Workability
This mitigation would require the major ownerships to commit sufficient resources to be able to undertake the monitoring and planning functions described above. As discussed in section 2.2, total average annual mortality of growing stock is currently 219 million cubic feet of timber. Of this total, 54 percent, or just under 120 million cubic feet, is attributable to insect and disease attack. Capturing even a small percentage of these losses as a consequence of this mitigation could fund significant monitoring and planning efforts.

The major ownerships, forest industries, logging industries and the state should initiate programs to identify and promote the use of harvesting equipment and harvesting techniques that can minimize damage to retained trees and to the soil.

Effectiveness
Equipment that is potentially suitable has been described in the Harvesting Systems background paper (Jaakko Pöyry Consulting, Inc. 1992b). Systems that rely on cut-to-length wood can significantly reduce the level of damage to residual stems by eliminating the need to skid tree length (topped and trimmed logs) or full tree (tree length with top and branches intact) logs which often wound the trunks of retained trees. Use of boom type harvesters and appropriate operating techniques can also reduce impacts to retained trees. In addition, by delimbing and topping trees in front of the machine it can be operated on a mat of vegetation that reduces damage to soil and roots. These types of equipment are in common usage in Nordic countries and other parts of the world. These benefits would only become available in the medium term as new equipment is substituted for older equipment.

Workability

Changing the type of harvesting equipment used which is the second aspect of the mitigation alternative would be more difficult to achieve. Minnesota's logging industry is characterized by many small operations, with typically less than 5 employees, and which operate with comparatively old equipment (Jaakko Pöyry Consulting, Inc. 1992b). This means it is unlikely the logging industry will have the resources to develop this initiative. Therefore, the wider forest community should be involved. Leadership will be required to initiate and coordinate this process. The MNDNR is the most suitable state agency to undertake this role. Funding should be sought from forest industry, county, state and federal sources. The logging industry could contribute by participating in trials of candidate systems. Changing the type of equipment used will be less feasible.

Logging equipment operators and tree cutters should be trained to practice techniques that minimize damaging retained trees during multiple entry harvesting operations.

Effectiveness

The newer types of harvesting equipment described above will be introduced over the short to medium term. This mitigation would reduce damage in the short term. There are a range of techniques to reduce damage such as: *directional tree felling* that enables fellers to aim trees to avoid damaging retained trees during felling; and use of *bump trees* to take the brunt of damage during the skidding operation and which are then cut. This would require education of logging crews and field supervisors.

In addition to education, specifications setting out maximum levels of damage to retained trees should be incorporated into logging contracts, and be specified as part of the amended and wider ranging Minnesota best management practices (BMPs) code of harvesting practices.

Workability

Changing techniques by training is feasible and is comparatively inexpensive. In other parts of the world there are numerous examples of regional logging industries pooling resources to form training organizations that are aimed at improving the work skills of the region's forest workforce. These organizations are typically funded by the logging industry, forest products industry and government sources. Significant improvements to worker safety are also achieved by improving worker training. This alternative could be incorporated into broader logger education programs aimed at improving the level of compliance with BMPs generally. Incorporation of these measures into a broader Minnesota BMPs code is likely the most workable approach. Invoking specific contract clauses would require significant commitments to monitoring and would therefore be less workable.

**5.3.2
Strategies to Monitor Forest Pest Populations**

> *The Forest Health Management (FHM) program should be actively supported
> by all major timberland ownerships in addition to the support being given by
> the MNDNR and USDA Forest Service.*

Effectiveness

Pest problems are a community problem and the responsibility should
therefore be shared. The county and forest industries should actively
participate in this program as an effective way of bringing additional
resources to monitor pest populations. This measure gains added urgency in
view of the likely introduction of gypsy moth into Minnesota, which will
undoubtedly have very significant impacts on industry and all forest
ownerships. The monitoring program should be linked to intervention plans
as discussed below.

Workability

The potential losses due to pest and diseases were identified previously. This
mitigation would provide additional resources to obtain a wider coverage of
timberlands as well as increased recognition of the potential impact pests can
have on forest productivity and nonconsumptive uses of forest resources.

**5.3.3
Strategies to Develop Intervention Plans**

> *The state should initiate and oversee a process to develop integrated pest
> management strategies for the major pests likely to increase as a consequence
> of timber harvesting; and for the gypsy moth.*

Effectiveness

As discussed above pests are a community problem, particularly those species
that are prone to major outbreaks. Development of regional, statewide and
interstate IPM strategies in advance of pest outbreaks allows time for all
parties to come to agreement on the types of intervention that are
appropriate; the circumstances under which the various methods of
intervention can be used; and responsibilities and cost sharing arrangements
that should apply where outbreaks occur. Gaining the level of support for
these strategies will require the active participation of representatives from
the following categories or groups: forest industries; timberland and other
forest ownerships; the resort and tourism industries; conservation groups; and
State Department of Agriculture. A leadership role is required to initiate this
process and to implement its findings. The MNDNR is the most appropriate
state agency with responsibilities that extend over many of the aspects of
Minnesota's forests likely to be affected by pest outbreaks.

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Development of these endorsed IPM approaches will reduce the potential for conflict at the time when early, decisive action can be the most effective approach.

The process used to develop the *Memorandum of Agreement regarding the aerial herbicide spraying program of the Division of Forestry, MNDNR* provides a precedent for the development of this initiative. This process proved to be unsuccessful in practice; however the experience gained in that effort could be a valuable lesson in how to shape the process needed to develop IPM strategies.

Measures should be taken to increase our knowledge of forest pests and to complete basic and applied research on our most serious pest problems.

Effectiveness
We currently do not have complete understanding of many host-parasite situations. Management strategies that are developed without the essential information concerning the biology of the pest and their interactions with the environment, host, and other organisms are doomed to failure. We must increase our understanding of these complex disease situations if we expect to control them successfully.

Workability
This measure depends on sources of funding for such work. Funding agencies at state and national levels must recognize the importance of research to understand forest health problems, and must also recognize that the payoff of such work may be long-term. Quick answers are not always possible, but solutions so developed are likely to have long-term effectiveness.

5.3.4
Strategies to Increase Use of MNDNR Insect and Disease Pest Management Guidelines

The MNDNR should make copies of the pest management guidelines readily available in a form that can be applied by all ownerships, field supervisors and loggers. This should be backed by an increased emphasis on forest health issues as part of the existing forest extension programs.

Effectiveness
Wider application of the guidelines would reduce the incidence of certain pests statewide. Extending the use of these guidelines would require modifications to make them more simplistic and straightforward to apply. This would be necessary to enable their use by forest owners, supervisors and loggers. Many of these categories of people will likely have limited understanding of forest management. The guidelines should be linked to extension programs aimed at logger training and provision of advice to NIPF

landowners. The reasons for targeting these categories of people are that they are responsible for many of the decisions that directly affect the vulnerability and susceptibility of stands, especially during harvest; and these categories are the least likely to have the knowledge to make informed decisions on these matters.

Workability
This mitigation would require the MNDNR to invest additional resources to modify and disseminate the guidelines. The increased extension efforts would also require additional resources. As discussed in the report, it is unlikely that owners will invest in pest control for their forests. Therefore, prevention of future infestations by the wider adoption of appropriate practices is a particularly cost effective way to improve overall forest health in the state.

6
PREFERRED MITIGATION STRATEGIES

A variety of strategies can mitigate against adverse impacts of timber harvesting and forest management activities. The final criteria document (Jaakko Pöyry Consulting, Inc. 1992e) describes how such strategies would be identified and selected. The identification of strategies is described in the earlier section 5, Potential Mitigation Measures to Address Identified Significant Impacts.

Framework for analyzing mitigations and selecting preferred mitigation strategies
Criteria for selecting strategies are drawn from the final criteria document noted above and reproduced below:

Based on an analysis of mitigation alternatives identified, preferred mitigation strategies will be selected by considering in relative terms:
1. the effectiveness at mitigating the identified significant impacts;
2. the beneficial effects on other resource values;
3. the adverse effects on other resource values;
4. the physical, biological, administrative (implementation and oversight), financial (costs, public and private, direct and indirect), and social (ability to organize, support and effect implementation) feasibility; and
5. the probability of success and duration of success.

In practice, the verbal and written input from the Advisory Committee on the potential mitigation strategies led to acceptance, rejection and/or refinement of the potential strategies. These results were then approved by the EQB and

comprise the strategies considered and evaluated in detail. Additionally, for this analysis the above criteria were grouped as follows:

1. *Effectiveness* addresses a mitigation strategy in terms of its ability to either avoid or reduce the identified impacts.

2. *Feasibility* addresses the likelihood that the mitigation strategy can be implemented, based on existing or future economic, social, biophysical, or administrative constraints.

3. *Duration* of mitigation can best be scored into four classes: 1=long-term—greater than 50 years; 2=medium-term—10 to 50 years; 3=short-term—2 to ten years; 4=very short-term—less than 2 years.

4. *Concomitant effects* refers to those strategies that have the potential to significantly affect other resources. It is clearly fallacious to consider that any forest management practice will only affect a single resource; forests are intricately interacting ecosystems, and each practice affects many resources.

5. *Probability of success*, though not tabulated explicitly in the following tables, is a combination of effectiveness, feasibility and duration with minimal negative concomitant effects. The strategies identified as highly effective, highly feasible, of long duration and with minimal negative concomitant effects are assumed to have the greatest chance of success in the long run.

These criteria were then applied to the various mitigation strategies for the purpose of comparison among them and to help determine preferred mitigation strategies. A variety of strategies can mitigate potential adverse impacts of timber harvesting and forest management activities on forest health. A comparison of the strategies considered is summarized in table 6.1.

Explanations of the ranks for these mitigation strategies are as follows:

Monitoring and if required manipulating the proportion of forest type groups that are maintained in susceptible and/or vulnerable age classes would be an effective way to anticipate medium term changes in the incidence of certain pest outbreaks. The age class structure of a forest can only be changed over the medium to long term. It is therefore important to have a clear understanding of trends as early as possible to allow the maximum time to effect changes. While the alternative would be of value in the medium-term, because of the time necessary it would be of marginal effectiveness in the short-term. The alternative is feasible in that the data needed to undertake such analyses are periodically available, as are the tools needed to derive the

relevant information. If implemented, this mitigation would provide a long-term benefit.

Table 6.1. Evaluation of mitigation strategies for minimizing negative impacts of timber harvesting on forest health. Rankings for effectiveness and feasibility from 1=high to 3=low, and for duration from 1=long- to 4=very short-term. Concomitant effects refers to potential positive (+) or negative(-) effects on issues of concern from the FSD.

Mitigation Strategy	Effectiveness	Feasibility	Duration[a]	Concomitant Effects (±)[b]
Monitor and/or manipulate age class distribution	2	1	1	Productivity (+)
Changing harvest equipment	1	1	1	Economic (-); Soils (+)
Worker training	1	1	1	Economic (+)
Monitor pests	1	1	1	
Develop IPM strategies	1	1	1	
Increase use of pest management guidelines	1	2	1	

[a] 1=long-term—greater than 50 years; 2=medium-term—10 to 50 years; 3=short-term—2 to ten years; 4=very short-term—less than 2 years.
[b] Effects that are noted are those with potential to *significantly* affect another resource.

Changing harvesting equipment is potentially an effective mitigation that would reduce the incidence of pests that benefit from damage of retained trees.   As discussed previously, logging contractors in Minnesota are typically small and therefore are unlikely to have the resources to experiment or to readily adopt new types of equipment that would involve extensive operator training. However, if a regional perspective is adopted with support from other stakeholders including forest industries and major ownerships; then the alternative will likely be very feasible. The benefits would extend from towards the end of the short-term to the long-term.

Worker training is an effective way to mitigate impacts caused by damage to retained trees. This is a comparatively inexpensive alternative that also has significant benefits in terms of worker safety and compliance with BMPs. Benefits can be realized in the short-term and would extend to the long-term.

Strategies to monitor forest pest populations are an effective way to give forest managers more time to react to likely pest problems and also a better appreciation of the extent of the problem.   Both are crucial pieces of information when choosing between alternative management responses. This

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mitigation alternative is feasible. This alternative would provide long-term benefits.

Development of IPM strategies for major existing and likely pests would be effective by allowing a faster and more focussed response than would likely occur if plans to deal with pest outbreaks are formulated during or immediately prior to an outbreak. This alternative would be most effective if linked to the monitoring programs set out in other alternatives. The mitigation is potentially very feasible assuming that a body is convened to develop this initiative. The benefits of this initiative would extend from the short-term to the long-term.

Increased use of pest management guidelines, especially by those ownerships who do not currently have access to this information, would be moderately effective. The effectiveness of the guidelines would be limited due to problems caused by the lack of professional judgement that may be required. It is also only moderately feasible because of the difficulties of disseminating the information to landowners in the NIPF category. It would be more feasible to educate loggers and other field staff. The duration of the mitigation would be short- to long-term.

Preferred Mitigations
The mitigation strategies set out above are not mutually exclusive and there is no strategy that is preferred as the strategies presented each tackle a slightly different angle of the forest health problem. As described above, all are moderately to highly effective and feasible and all would provide long-term benefits.

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APPENDIX A.

REVIEW OF THE LITERATURE -- FOREST INSECTS

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A.1
SPECIFIC FOREST INSECT PESTS

A.1.1
Forest Tent Caterpillar - Malacosoma disstria Hubner

Forest tent caterpillar (FTC) is a native, univoltine insect found throughout much of the U.S. and Canada. It is an especially important defoliator of aspen in the Lake States, but also damages oaks, sugar maple, basswood and other hardwoods. FTC also feeds on many shrubs and may exhibit a preference for hazel (Corylus spp.) (Duncan et al. 1956).

Life History
Many aspects of FTC life history and population dynamics were intensively studied in Minnesota by Witter and colleagues. The following information in this section was derived from Witter (1979), unless otherwise noted.

In Minnesota, mating and oviposition occur from early to mid-July. Each female lays a single egg mass in a cylindrical band around small aspen twigs. Egg masses may contain a few to 500 eggs, but usually average ca 200. Egg masses are distributed predominantly in the upper and middle crown. Pharate larvae within eggs overwinter until the following spring. Larvae emerge in late April to late May, depending on climatic conditions. Larvae pass through five stadia, completing development in 5-8 weeks. Larvae are quite gregarious, and may feed, rest and molt in groups, particularly during the first 3 instars. Forest tent caterpillars do not spin a tent, but will form silken mats on leaves, branches or boles where they congregate when resting or molting (Batzer and Morris 1978). Complete defoliation of trees commonly occurs in June. Heavily defoliated trees refoliate by late July (Batzer 1972). Larvae spin cocoons in rolled leaves of aspen trees in mid- to late-June for pupation. When defoliation is severe, however, cocoons are found on non-host trees, shrubs, and ground vegetation. Adults emerge from cocoons in 2-3 weeks.

Extensive studies of FTC population dynamics were conducted in Minnesota. Witter et al. (1975) examined FTC populations during an outbreak that began in the late 1960's and persisted through the mid-1970's. They found that variation in survival from egg to 30-day larvae (S1 stage) and survival of 30-day larvae to adult (S2 stage) had the greatest influence on subsequent egg density. They also observed S2 tended to change in an opposite direction from S1. The net result produced a relatively constant number of eggs per unit area, unless populations were drastically lowered by a severe disruption. Daily mortality rate for larvae over all years and plots averaged 5%. Miller and Epstein (1986) cite unpublished evidence indicating larval densities may decrease by 25% a day during outbreaks.

Egg mortality from parasitism, infertility and death of pharate larvae in eggs was documented in several studies. Egg parasitism is generally low and

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unaffected by population density (Witter and Kulman 1979). Infertility is highly variable; infertility rates ranged from 1-3% (Witter and Kulman 1972b) up to 33% (Hodson 1941). High infertility rates in 1936 coincided with extremely warm weather (38-42° C) during adult emergence and oviposition (Hodson 1941). Annual pharate mortality is also highly variable, ranging from 1 to 90% (Witter and Kulman 1972b), and is strongly influenced by cold winter temperatures (Hodson 1941, Hanec 1966, Ives 1973).

Weather conditions may also strongly influence early larval survival. Collapse of several outbreaks has been related to one or more factors such as cold temperature, rain, snow, wind and absence of foliage due to frost acting on young larvae in the spring (Sweetman 1940, Hodson 1941, Blais et al. 1955). Ives (1973) reported that FTC population increases were usually associated with cool winters and warm springs. Collapse of outbreaks was often associated with warm winters and cool springs. High mortality of pharate larvae was associated with winter temperatures below a threshold of -42° F (Batzer and Morris 1978). Raske (1975) suggested sudden population collapses may be related to cumulative interactions between low temperatures and sublethal presence of pathogens. A nuclear polyhidrosis virus apparently caused the collapse of one FTC population in the first year of outbreak (Stairs 1964).

Factors affecting survival of late-stage larvae are difficult to quantify because of wandering larval behavior. Late instar larvae often wander in search of food or suitable pupation sites, hence the common name of "armyworms" (Batzer and Morris 1978). Starvation may be an extremely important mortality factor when egg density and early larval survival is high (Hodson 1977). Parasitism rates of fourth and fifth instar larvae by Tachinid flies ranged from 3-23% (Witter and Kulman 1972b). Pathogens may also cause mortality, especially where humidity is high (Stairs 1972). Lindroth and Bloomer (1991) used laboratory bioassays and artificial diet to examine effects of protein and secondary compounds on larval survival and development. They suggested variability in relative concentrations of foliar nitrogen and phenolic glycosides may be involved in differential susceptibility to FTC defoliation among aspen clones. Population density may also affect larval performance. Larvae reared at high population densities in a laboratory setting attained lower biomass and took longer to develop than larvae reared in less dense colonies (Muggli and Miller 1980).

Parasitism of pupae may be a particularly important mortality factor, especially in late stages of outbreaks. During the third or fourth year of an outbreak, pupal parasitism may approach 90% (Hodson 1941, Sippell 1957). Sarcophagid and Tachinid flies account for nearly all pupal parasitism (Witter 1979). Sarcophaga aldrichi Parker is the most common parasite in the Lake States and may account for 75% of cocoon parasitism (Hodson 1941, Sippell 1957). Pupal parasitism combined with starvation or poor weather conditions can result in collapse of outbreaks.

Fecundity may decrease as epidemics progress. Sex ratio may progress from 1:1 in the first year of an outbreak to 2:1 (males to females) in later years (Witter 1979). Fecundity ranged from 122-236 eggs per mass during a 1967-1972 outbreak in Minnesota. Average fecundity was highest in 1968 and 1969 and lowest in 1970 (Witter et al. 1975). No information on adult dispersal is available.

Witter (1979) concluded that important factors regulating collapse of FTC outbreaks include 1) pharate mortality from low winter temperature; 2) early larval mortality due to unfavorable spring weather; 3) late larval mortality from starvation and 4) pupal parasitism by Sarcophaga aldrichi. Witter (1979) presents a table showing factors causing population collapse in various regions of North America.

Impact
Outbreaks of FTC in Minnesota have likely occurred for hundreds of years. At least nine outbreaks have been documented since 1891 (Hodson 1941, 1977, Witter et al. 1975, Witter 1979, Minnesota DNR Ann. Ins. Dis. Rep. 1978-89). Outbreaks normally last 3-4 years, although some persist for 5-8 years or longer. Intervals between outbreaks have ranged from 6 to 16 years. Annual reports from the Minnesota Department of Natural Resources indicate two widespread FTC outbreaks have occurred since 1977. An outbreak that began in 1977 peaked in 1980, with 4.7 million ac of defoliation, then collapsed in 1980. All hardwood species except red maple sustained defoliation. Population collapse was attributed to Sarcophagid parasitism, a cold wet spring and starvation. Populations were generally low until 1986, although localized areas sustained epidemic populations for nine or more years. Populations were very high from 1987-1990 and began to decline in 1991. Aspen, basswood and northern hardwood stands sustained up to 100% defoliation. Addy et al. (1971) developed a rating system and demonstrated that estimated impact of FTC exceeded that of all other forest insects in the north-central U.S. Areas of up to 100,000 mi^2 have sustained FTC defoliation in a single year (Davidson and Prentice 1968).

Growth loss resulting from FTC defoliation tends to be more significant than mortality (Kulman 1971). Most studies have found direct mortality from FTC defoliation to be negligible or to be concentrated in small, suppressed trees (Kulman 1971, Batzer 1972). Witter et al. (1975) studied an outbreak in northern Minnesota that lasted from 1964-1972. Egg mass densities ranged from 1-9 million/ac from 1968-1971 and trees in all plots were completely defoliated. The authors observed a 41% decrease in tree stem density and 27% reduction in basal area. They attributed these significant losses to the duration of the outbreak, which persisted 5-7 consecutive years instead of the typical 3-4 years. Mattson and Addy (1975) suggested forest productivity would be most severely affected after 5-6 years of defoliation.

Two or more years of heavy defoliation following one year of light defoliation is a common scenario during FTC outbreaks (Duncan et al. 1956, Duncan and Hodson 1958). In Minnesota, this scenario resulted in 72-87% reduction in basal area growth in 40-year-old or younger aspen stands (Batzer 1955, Batzer et al. 1954). Duncan et al. (1956), also working in Minnesota, observed basal area reduction of 70 and 90% during the first and second years of heavy defoliation following one year of light defoliation. These authors determined that in average stands where net annual growth was ca 0.33 cds/ac, loss due to FTC defoliation would translate into an average loss of ca 0.6 cds/ac. A fully stocked stand on a good site with net annual growth equal to 1.3 cds/ac would be expected to lose 2.25 cds/ac during a typical FTC outbreak. Growth reductions of 16-22% were recorded the year after the outbreak had collapsed, in areas where previous defoliation had been heavy (Duncan et al. 1956, Duncan and Hodson 1958). Growth rates returned to normal two years after collapse of the outbreak. During a 1950's outbreak in western Canada, growth reduction amounted to a loss of 2 cds/ac over 1.5 million ac (Hildahl and Reek 1960). Defoliation of 25 and 100% reduced aspen growth in Michigan by 38 and 67%, respectively (Kulman 1971). Complete defoliation of aspen in Ontario studies resulted in growth reduction of 80% (Rose 1958). Rose (1958) found defoliation caused growth to cease within two weeks in a 60 year-old aspen stand in New Brunswick. Growth resumed after refoliation. However, growth reductions of 42, 52 and 77% were sustained during the three years of defoliation.

Tree mortality seldom results directly from FTC defoliation (Kulman 1971). However, long-term and follow-up studies showed mortality from pathogens and unknown sources were related to defoliation intensity and duration (Churchill et al. 1964). Anderson and Martin (1981) examined the incidence of Hypoxylon sp. cankers in northern Minnesota aspen stands over an 8 year period. Length and intensity of FTC defoliation during an outbreak prior to the study was significantly associated with the incidence of new cankers. Crown dieback and shoot mortality may result from FTC defoliation and may affect up to 25% of the crown (Batzer et al. 1954). Twig dieback may be most severe on suppressed trees (Duncan et al. 1956). Refoliated leaves tended to be smaller than normal (Duncan and Hodson 1958).

An interesting result noted by Duncan et al. (1956) was that balsam fir growing beneath an aspen overstory significantly increased radial growth during FTC defoliation. However, the increase in balsam fir growth was less than one-third the decrease in aspen growth and would not offset aspen volume loss. Duncan et al. (1956) also examined impacts of FTC feeding on understory species. Although hazel was preferred and frequently fed on by larvae, neither stem mortality nor twig dieback was observed.

Defoliated trees, swarms of caterpillars and abundant frass may impact recreation during FTC outbreaks, but effects have not been quantified. Sarcophagid parasites (known as flesh flies) are often abundant in later years of FTC epidemics. Although the large, hairy flies do not bite, they

frequently swarm and settle on peoples' heads and faces, causing considerable annoyance.

Contributing Factors

Relative little information is available regarding site or stand-related factors that contribute to FTC outbreaks. Harmsen and Rose (1983) noted the difficulty of finding FTC caterpillars during intervals between outbreaks. They presented preliminary evidence indicating that endemic FTC populations were confined to wet, lowland forested areas due to differential mortality between wet and dry forest habitat. The authors suggested this differential mortality arose because of the inability of ground predators to attack caterpillars on lowland trees and greater mortality of FTC parasites in marshy areas. Witter et al. (1975) found severe FTC damage was associated with low elevation sites where high water tables prohibited normal root development. Duncan and Hodson (1958) reported tree mortality averaged 20% during a 1933-1938 FTC outbreak that coincided with severe drought in the mid-1930's. Tree age may affect vulnerability to FTC. Barter and Cameron (1955) observed substantial mortality in 60-year-old aspen following three years of FTC defoliation.

Management and Control

Outbreaks of FTC are usually terminated by starvation, natural enemies and unfavorable weather (Davidson and Prentice 1968). Witter and Kulman (1972a, 1979) reviewed the parasite complex (which includes 40 species) and predators of FTC. Possibilities of developing a fungal pathogen for biocontrol of FTC were discussed by Perry and Fleming (1989). Few workers have discussed FTC in the context of forest management. Witter (1979) recommended an integrated pest management program for FTC that included annual aerial survey or egg mass survey to determine current defoliation level, educational programs for the public during outbreaks, and inspections of mature and overmature aspen stands during FTC outbreaks by forest managers. Sampling techniques for FTC life-stages and defoliation were developed by Witter and Kulman (1969), Shephard and Brown (1971), Witter et al. (1972, 1975), and Nyrop et al. (1979). Batzer and Morris (1978) suggested that an average of 19 egg masses per tree (trees over 6 inch dbh) indicated the likelihood of complete defoliation. Natural enemies and weather-related factors generally cause FTC epidemics to collapse. However, application of chemical or microbial insecticides may be appropriate in some situations. For example, aerial applications of Bt or Dimilin have been used recently on federal lands in the Lake States to protect recreation areas and high value stands of mature red oak (Michael Connor, USFS, S&PF, pers. comm.). Johnson and Morris (1981) evaluated effectiveness of various compounds and formulations for FTC control. Direct control of FTC in Minnesota has also been carried out in popular recreation areas and by private landowners in Minnesota, according to annual reports of the Minnesota Dept. of Natural Resources.

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A.1.2
Large Aspen Tortrix - Choristoneura conflictana Walker

Life history
Large aspen tortrix (LAT) is a native, univoltine defoliator of aspen. Other species, including paper birch, willow and cottonwood, are occasionally fed upon. Outbreaks may persists 2-3 years, often preceding outbreaks of forest tent caterpillar, then collapsing when forest tent caterpillars build.

Second instar larvae overwinter in hibernaculae and emerge in spring when aspen buds begin to swell, ca ten days before leaves appear. Young larvae mine buds, while older larvae web leaves together and feed within folded leaves. Cold or wet weather, tight buds or dispersal loss may cause mortality to early larvae (Coulson and Witter 1984). Pathogens in Ontario populations were surveyed by Burke and Percy (1982). Larvae pass through 5 instars, pupating in mid-June on the tree. Adults emerge in about ten days, mate and oviposit on aspen leaves or other available surfaces. Larvae hatch from eggs in ca two weeks and feed on the epidermis of webbed leaves. In mid-August, larvae cease feeding and spin hibernaculae on bark or protected sites.

Impact
Defoliation can reduce radial growth rates. Outbreaks seldom persist long enough to cause mortality. Large amounts of silk may be present in severe infestations and may be annoying to people walking through aspen forests. Defoliated trees generally refoliate later in the summer, but leaves may be smaller and sparse. Outbreaks occurred in various regions in Minnesota in 1984-1987, generally in areas where forest tent caterpillars were not present (Alan Jones, MN DNR, pers. comm.). Populations appeared to be collapsing in 1988-1989, probably due to widespread defoliation by forest tent caterpillar.

Contributing factors
Little information is available on site or management-related factors contributing to epidemic populations of LAT.

Management and Control
Birds, especially chickadees, may feed on larvae and may be a factor in LAT population dynamics (Ives 1981). Starvation may be the most important factor causing population crashes. Heavy defoliation may cause larval mortality and reduced fecundity, and may eliminate suitable oviposition sites (Beckwith 1968, 1973, Ives 1981). Several species of parasites may attack eggs, larvae and pupae, but importance of parasitism in the Lake States is not well-known. Occasionally, chemical or microbial insecticides may be applied in high-use areas. Pest management techniques are usually not required since populations normally crash in 2-3 years (Coulson and Witter 1984).

A.1.3
Bronze Birch Borer - Agrilus anxius Gory

Much of the information below was derived from Akers (1985) and Wilson and Haack (1990), unless otherwise noted.

Life cycle

Bronze birch borer (BBB) is a native borer and is a significant pest of forest and urban birch throughout Canada and the U.S. Adults emerge from infested trees from late May to mid-July in the Lake States. They feed on aspen and other hardwood foliage for about a week, then fly to birches where they mate. Eggs are laid in bark fissures and in dark patches over thin bark. Larvae hatch in 1-2 weeks, bore into the cambial region and construct irregular, zig-zag galleries. Most larvae pass through four instars, complete development by autumn, then burrow into the sapwood where they overwinter in chambers. Pupation occurs the following spring. BBB may require two years to complete its life cycle in the northern edge of its range. Anderson (1944) observed life cycle of BBB in Minnesota varied between one and two years.

Impact

Larval feeding in the cambial zone disrupts conduction of food and water in the tree. Larvae damage only the outermost growth ring of sapwood in a single year. Since water is transported through several sapwood rings, 2-3 years of successive attack may be needed before any branch dieback occurs.

First evidence of BBB attack is browning of foliage on infested areas, followed by dieback of branches in the upper crown. Decline may continue for 2-3 years, before trees eventually die. Presence of swollen, knobby and irregular ridges on bark resulting from larval tunneling, irregular galleries under the bark and D-shaped emergence holes of adults are indicative of BBB attack. Bark ridges and exit holes may precede crown dieback by 1-3 years. Trees with over one-third of the upper crown dead or dying will generally succumb.

Contributing factors

Trees stressed by drought, defoliation, disease or other injury are most susceptible to BBB attack. Susceptibility also varies among species and varieties, although reports of resistance often conflict (Miller et al. 1991). Healthy, vigorous paper birch may resist BBB, but is much more susceptible than river birch. Yellow birch is moderately susceptible. Anderson (1944) examined aspen-birch forests in northern Minnesota. BBB appeared to be attracted to decadent and dying trees. Barter (1957) showed that larvae could not survive in healthy trees but required hosts stressed by previous BBB attack, defoliation, adverse weather or old age. Odiferous products of biodegradation may attract adults (Carlson and Knight 1969). Although crowns may die from the top down, highest populations of BBB larvae were

found in the bole, main stem and live branches near the stem junction (Ball and Simmons 1980).

Management and Control
Management should be directed at preventing stress and maintaining vigorous trees. Even-aged birch stands should be clear cut when trees are merchantable. Residual trees may be highly susceptible to attack in partial cuts or when other species are selectively removed in mixed stands (Balch and Prebble 1940, Swaine 1918). In mixed stands, mature and defective birch should be removed. High value stands should be thinned to encourage vigorous growth of young trees. Dying trees should be cut and removed prior to adult emergence. Electrical resistance was measured with a Shigometer and may be used to determine susceptibility of individual trees (Ball and Simmons 1984). Infested trees can also be used as trap trees, left until July or August, then removed and destroyed. If infested material cannot be removed or burned before adults emerge in spring, it should be stacked under airtight tarps until adult emergence is complete. Borer populations will generally not build-up in logging slash.

Woodpecker predation may contribute to BBB regulation. In one study in Pennsylvania, woodpeckers reduced overwintering larval populations by up to 60% (Loerch and Cameron 1983). Egg parasitism of 7-10% was observed in Pennsylvania (Loerch and Cameron 1983). Larval parasitism by five parasitic species totalled 18%.

A.1.4
Gypsy Moth Lymantria dispar Linnaeus

A vast amount of literature related to gypsy moth (GM) has been generated and an exhaustive review was well beyond the scope of this project. An attempt was made to review significant aspects of GM bioecology, impact and management most relevant to Minnesota and this project.

Life History
Detailed descriptions of gypsy moth biology are provided by McManus (1987), Montgomery and Wallace (1988), and in chapter 2 of Doane and McManus (1981). The following material in this section was extracted from these sources, unless otherwise noted. Gypsy moth overwinters in egg masses of 75-1200 eggs. Healthy populations contain ca 700 eggs/mass while declining populations average 250/mass (Montgomery and Wallner 1988). Eggs begin hatching in mid-April or May, depending on temperature and budbreak of host species. Although eggs within one egg mass hatch in 3-5 days, hatching in a given locality may occur over 2-8 weeks, complicating timing of control measures. In northern states, hatching is usually complete in 2-3 weeks. When weather is favorable, newly emerged larvae climb to tops or perimeters of trees, trailing silk threads continuously. Once larvae reach tree tops, they do not begin feeding, but drop on silk and

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are dispersed by wind. This is the only natural dispersal of gypsy moth. Larvae that hatch in inclement weather (e.g. precipitation or temperatures < 7°C) may remain near egg masses for several days, reducing their propensity for dispersal and overall viability (McManus 1987, McManus and Mason 1983, Montgomery and Wallner 1987). After dispersing, larvae begin feeding on foliage of acceptable host plants. Larvae complete 5 (males) or 6 (females) instars, each lasting 4-10 days. Young larvae alternatively feed and rest under leaves and beneath branches. In sparse populations, larval behavior changes when larvae molt to the fourth instar. Late instar larvae feed only at night, descending from canopies at dawn to rest in protected areas during the day. Larvae rest under bark flaps or in holes and wounds on tree boles, where they are protected from predators. Larvae will also rest beneath litter, rocks or stumps if protected sites on boles are unavailable. In dense populations, larvae do not descend trees, but remain in the canopy and feed intermittently through the day. When a host tree is completely defoliated, late instar larvae actively wander and search for food. In sparse populations, a typical female caterpillar will consume 1000 cm^2 of foliage. In dense populations, each larva will consume ca 170 cm^2 foliage (equivalent to about 3 red oak leaves). Consumption of oak foliage averages 10 mg for each mg gain in larval biomass (Valentine and Talerico 1980). Consumption increases with each instar; last instar larvae consume ca 75% of total foliage consumption (Nichols 1980). Larvae complete development and pupate on or near daytime resting locations such as tree bases, on ground litter, or in tree canopies if populations are dense. Adults emerge in 10-14 days, with males preceding females by 1-3 days. Sex ratio may be skewed towards males in dense populations (Maufette and Jobin 1985). Males fly in zig-zag patterns and actively search for females. Female moths have developed wings but do not fly. Females release a sex pheromone to attract males. Mating and oviposition occur within 1-2 m of the female pupation site (Odell et al. 1980). It should be noted that in a strain of GM in Japan, females are fully capable of flight (Schaefer 1978). Eggs are deposited in a secretion produced by female moths and covered with hair and scales from the females' body. Eggs are well-protected from desiccation and survive temperatures as low as -29°C (McManus 1987).

Spatial dynamics
Dispersal of GM life-stages has been intensively studied and relates to establishment of new infestations as well as host preference. Early workers believed first instar larvae could be transported up to 40 km by wind (Collins 1917). However, a model developed and verified by Mason and McManus (1981) showed that in flat areas, 99% of larvae were deposited within 1 km of their source area. In mountainous regions most larvae are deposited within 3 km of their source area (Mason and McManus 1981), although a few larvae may travel up to 19 km (Taylor and Reling 1986). Dispersal tendency of first instars is greater in the presence of unfavored hosts than when only favored hosts occur, increasing the chance that favored hosts will eventually be encountered (Capinera and Barbosa 1976). Short distance dispersal of late instar larvae seeking resting sites or new food sources is of

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considerable importance in host-switching behavior (Lance and Barbosa 1982). Early instars are most likely to become established on primary hosts, but later instars may move to less-preferred host species (Lance and Barbosa 1982, Rossiter 1987, Elkington and Leibhold 1990). This behavior also results in accumulation of late instar larvae on trees with large numbers of available resting sites such as bark flaps or wounds (Leibhold et al. 1986).

Human transport of egg masses or pupae is the most significant agent in long-range dispersal of GMs. Egg masses, the most long-lived stage of the GM life cycle, are frequently deposited on objects such as recreational vehicles, picnic tables, lawn furniture and trailers located in or near GM feeding areas. Introduction of GM into previously uninfested regions can easily occur when people from infested areas move or vacation in uninfested areas and inadvertently transport egg masses. Interstate dispersal of eggs can also occur via transport of infested nursery stock.

Since GM was introduced in 1869, it has expanded its range by more than 300 miles (Leibhold and Elkington 1990). However, spatial patterns of outbreak development are poorly understood. Outbreaks have been hypothesized to be initiated by immigration of larvae from nearby outbreak areas (Campbell 1976, Valentine and Houston 1979). GM outbreaks may begin in foci, such as ridgetops or drought areas, then spread into adjoining areas (Houston and Valentine 1977). Spatial analysis of population trends for 25 years in Massachusetts showed defoliation radiated out from apparent foci (Leibhold and Elkington 1989, 1990). However, initiation of outbreaks by wind-disseminated larvae was not supported. Leibhold and Elkington (1990) suggested defoliation patterns may instead reflect spatial distribution of susceptible stands.

Qualitative examination of GM infestation maps indicated GM has not spread to the north as rapidly as to the south and west. Range expansion models indicate regions with mean January temperatures of less than 7°C are infested more slowly than warmer regions (Leibhold et al. 1991). Leibhold et al. (1991) used models based on the spatial occurrence of infestation in North America since 1900 and climatological variables to predict rate of future GM expansion. Based on this model, natural expansion of GM into Minnesota is expected between 2015 and 2025 (Leibhold, pers. comm.). This, of course, does not preclude the possibility of infestations arising from accidental introduction of GM egg masses or other life-stages from into Minnesota.

Pheromone trap catches of male moths and spatial analysis were used to predict GM defoliation in Michigan. Trap catches in a grid across the state (2 traps/township) and regression analysis resulted in an 85% correspondence between observed and predicted defoliation (Gage et al. 1990).

Population dynamics

Elkington and Leibhold (1990) reviewed much of the literature related to GM population dynamics since 1981. Literature prior to 1981 was extensively reviewed by various authors in chapter 4, Doane and McManus (1981). The GM population system has four distinct phases and was described by Campbell (1981). The innocuous phase is stable and can be maintained indefinitely. Innocuous populations may range from 2-25,000 fourth instar larvae/ha. Processes that maintain low-density, stable populations are least effective along the advancing front of the GM infestation. A transient release phase enables a sparse population to expand to an outbreak mode. Outbreak populations are relatively stable and can be maintained up to 10 years. Outbreak populations may range from 250,000 to 2.5 million larvae/ha. Eventually, outbreak populations pass through a transient decline phase into the innocuous mode. The relatively stable innocuous and outbreak phases result in bimodal population dynamics.

Wallner and McManus (in Doane and McManus 1981) summarized factors contributing to GM population dynamics. Predation may be the most significant mortality factor affecting low-density populations. A nuclearpolyhidrosis virus (NPV) is generally the most significant factor affecting dense populations. The release phase of GM populations is typified by vigorous individuals, large egg masses and preponderance of female pupae. With favorable weather and suitable hosts, GM populations exceed predatory regulation due to their high reproductive potential. Outbreaks may proceed unimpeded for two to several years. Eventually, qualitative changes in hosts resulting from defoliation feedback on GM populations. Physiological stress of high density populations may alter pupal weight, fecundity, developmental period and survival, causing a steady decline from outbreak levels. Defoliation from high density populations may result in direct starvation of larvae or qualitative changes in foliage that reduce GM success (Wallner and Walton in Doane and McManus 1981). Adverse weather is also important to population decline. Lack of phenological synchrony between bud burst and egg hatch or spring frosts that kill new foliage reduce availability of foliage. Egg survival may be reduced by extreme overwintering temperatures and lack of snow cover, or when spring frosts follow extended periods of warming.

Parasites contribute to overall mortality but generally do not respond rapidly enough to prevent outbreaks from building (Campbell et al. 1977, Campbell and Sloan 1977). Some parasites are important at low GM population levels, while others may contribute to population stabilization or decline in post-outbreak years. Parasites may contribute to population collapse by vectoring disease agents, especially NPV (Podgewaite in Doane and McManus 1981). Extensive efforts beginning in 1905 to locate potential parasites of the GM and introduce them into North America are reviewed by Reardon and others in Doane and McManus (1981). Naturally occurring parasites were also surveyed intensively and many were reared for re-distribution. Attempts at inoculation or augmentation of native parasites were reviewed by Blumenthal

in Doane and McManus (1981). Recent studies indicate that a multi-voltine larval parasite, Compsilura concinnata may exhibit spatial, but not temporal, density-dependence (Elkington et al. 1990). Enhanced parasitism of dense GM populations could contribute to the apparent stability of low-density populations.

Daily migrations of large larvae in sparse populations up and down trees and their tendency to pupate in litter provides opportunities for predation of these stages by ground-dwelling predators (Weseloh 1990). At low population densities, generalist predators account for nearly all GM mortality (Weseloh 1990). Pupal predation by small mammals, particularly white-footed mice and shrews, may be the most important mortality factor (Campbell and Sloan 1977). Influence of small mammals and other generalist predators may be affected by availability of alternate food (Smith and Lautenschlager in Doane and McManus 1981). The importance of bird predation is unknown (Weseloh 1990). Ants may also exert some control, especially when larvae fall to the forest floor (Weseloh 1990). A carabid beetle, Calasoma sycophanta, is an introduced specialist predator that attacks GM larvae and pupae. In North America, GM mortality from Calasoma sp. appears sporadic and a lag of 1-2 years may be required before impacts are noticed (Weseloh 1990). Smith (1985) suggested management of food and cover for GM predators could enhance predator impact. Smith and Lautenschlager (in Doane and McManus 1981) reviewed information on a variety of GM predators.

The NPV is generally considered to be the primary regulator of dense GM populations in North America (Podgewaite in Doane and McManus 1981). Bacteria and other pathogens may also contribute to GM mortality, but their incidence rarely approaches that of NPV. NPV may be transmitted by natural enemies, through inter-generational infection of eggs and through contact with foliage contaminated by cadavers (Podgewaite et al. in Doane and McManus 1981). Two distinct waves of GM mortality from NPV may occur during larval development. Elkington et al. (1990a) suggested early instars acquired NPV from egg cases and cadavers of these larvae cause a second wave of mortality in late instars. Lewis, Podgewaite and other workers reviewed various aspects of NPV and development of microbial insecticides in Doane and McManus (1981). Recent research indicates that phenolic compounds in foliage may decrease susceptibility of GM larvae to NPV (Keating et al. 1988, Schultz et al. 1990). Phenolic levels may vary among tree species, seasonally and in response to defoliation. This variability may relate to stand susceptibility and GM mortality due to pathogens (Schultz et al. 1990).

Contributing Factors
Gypsy moth is tremendously polyphagous; early studies found larvae fed on 458 plant species and 86 of 169 tree species native to eastern North America (Forbush and Fernald 1896, Mosher 1915). Gypsy moth shows definite preferences for certain species, however, resulting in differential

susceptibility to defoliation among tree species. Mosher (1915) used laboratory choice and bioassay experiments to group 147 eastern forest species into 4 classes of preference. Houston (1979) separated 88 eastern tree species into five classes of preference. Classes 1-3 were considered most preferred, class 4 was intermediate and class 5 was least preferred. Species common in Minnesota and classified as most preferred included various oak species, aspens, paper birch, basswood, tamarack and willows. Other workers have similarly found that members of the genera Quercus and Populus tend to be highly favored by GM larvae. Campbell and Sloan (1977b) proposed an index of preference based on the ratio of defoliation sustained by 37 species relative to the defoliation of white oak. Utilization of preferred and avoided species may depend on the relative abundance of species in the infested stands (Lechowicz and Maufette 1983). An electivity index of feeding preferences was calculated in Quebec, on the northern edge of the GM range in North America, which accounted for relative foliage biomass of attacked species (Lechowicz and Jobin 1983). Results indicated Quercus rubra and Populus grandidentata were most preferred, but all 19 species tested were utilized to some degree. Mauffette et al. (1983) subsequently used the same electivity index on 14 sites in Quebec and found preferential attack of Quercus rubra, Amelanchier ssp., Populus grandidentata, Salix sp. and Ostrya virginiana. Gansner and Herrick (1985) weighted defoliation estimates by tree crown size and observed various Quercus sp and aspen to be most favored hosts in central Pennsylvania.

Identification of host preference is complicated by differences among regions and changing preferences of maturing larvae. Geographical differences in host preference are especially evident when intermediate species are considered. For example, Ostrya virginiana was strongly preferred in Quebec but was intermediate in New England studies. Early instar larvae tend to have narrower host ranges than older larvae (Barbosa 1978). Host preference of first instars may be related to phenological synchrony between budbreak and egg hatch (Barbosa et al. 1979). Utilization of less preferred hosts is more common in late instars (Houston 1979). High competition among larvae during outbreaks can also increase utilization of intermediate and less-preferred hosts (Campbell and Valentine 1972, Campbell and Sloan 1977). Exploitation of less preferred hosts may allow late instars to avoid high levels of density-dependent mortality, such as starvation or disease (Rossitor 1987).

Site and stand conditions may influence GM performance and ability of larvae to use various host species. Differences in suitability of potential host plants may affect weight, development rate, survival, fecundity and behavior (Martinat and Barbosa 87). Generally, acceptability of various host species parallels their suitability for larval growth and development (Martinat and Barbosa 1987, Elkington and Leibhold 1990 and references therein). Martinat and Barbosa (1987) suggest alkaloids or other defensive chemicals may deter feeding by GMs. Feeding deterrents are likely to regulate host plant selection of polyphagous insects, while feeding stimulants may regulate

host choice of monophagous or oligophagous insects. Lechowicz (1983) examined a suite of foliar characteristics of trees in Quebec and suggested trees with high sugar:tannin rations in foliage were preferentially attacked. Other traits such as leaf toughness, nutrients, and phenology were also important, though. However, no single allelochemic or nutritional factor can explain GM performance or host preference. Host preference likely arises from a complex interaction of allelochemical, nutritional and physical attributes of foliage (Elkington and Leibhold 1990). Defoliation can induce changes in many foliar attributes; such changes may subsequently affect larval development, survival and pupal weight (Elkington and Leibhold 1990). Schultz and Baldwin (1982) suggested foliage quality may be linked to initiation and collapse of outbreaks.

Factors other than host species can also affect GM host preference and subsequent performance. Pioneering work by Bess et al. (1947) demonstrated that severely defoliated stands in New England tended to occur on dry, open sites with light, sandy soils. These sites were further characterized by slow-growing trees, light leaf litter and a history of fires. Additionally, heavily defoliated stands typically produced more refuges such as bark flaps and wounds where resting larvae could escape predation. Campbell et al. (1975) similarly found trees on low moisture sites provided more protection for resting larvae and tended to sustain heavier defoliation. Presence of structural features such as bark flaps, large dead branches, deep bark fissures and holes has been quantified to assess susceptibility to GM defoliation (Houston 1979, Valentine and Houston 1979). Houston (1979) described features and provided examples of susceptible and resistant stands. Stands with high frequency of preferred species, structural features, frequent disturbance, or located on dry, rocky sites or on ridges tended to be most susceptible. Stands with vigorous trees (even if dominated by preferred species), growing under more mesic conditions tended to be resistant. In New Jersey, oak mortality due to GM defoliation was greatest on sites with southern aspects where moisture stress was high (Kegg 1973). An association between tree mortality and low vigor or poor crown condition prior to defoliation has been reported by several workers (Campbell and Sloan 1977, Herrick 1982, Gansner and Herrick 1982). In contrast, mortality of red oaks was higher for trees on moist and mesic sites than for trees on xeric sites (Statler and Serrao 1983). Quimby (1987) reported disproportionate mortality of valuable trees on high quality sites in Pennsylvania. Quimby speculated that smaller root systems or increased presence of Armillaria accounted for high mortality of trees on mesic sites. These results were corroborated by Hicks (1984) who observed a direct association between mortality and site index in stands in Maryland and West Virginia.

Risk/Hazard rating
Continued spread of GM into new geographical regions and different forest situations has stimulated much interest in predicting susceptibility and vulnerability of forests. Susceptible stands refer to those stands likely to be

infested and defoliated by GM (high risk). Vulnerable stands (high hazard) are those stands likely to sustain damage such as mortality, growth loss or reduced reproductive capacity when GM defoliation occurs (Hicks and Fosbroke 1987). Risk/hazard rating allows resource managers to target stands where detection and survey efforts, direct suppression, silvicultural treatment or salvage should be concentrated (Hicks and Fosbroke 1987). Identification of susceptible stands may also help managers locate focal sites, where GM populations can build-up and spread into more resistant areas (Valentine and Houston 1981, Houston 1983).

Houston and Valentine (1977) developed discriminant function equations to predict susceptibility based on data from New England stands with known histories of defoliation. Variables used in the equations included presence of structural features such as bark flaps, holes and wounds, bark fissures, crook and sweep, and abundance of preferred and other species. These variables proved difficult and expensive to measure, so the system was subsequently revised (Valentine and Houston 1984). Two discriminant functions were developed. One system required data on size and basal area of preferred species and presence of bark flaps and fissures. The second system required only inventory data on size and basal area of preferred hosts relative to nonpreferred hosts. Rates of misidentification were ca 10% greater for the second system than the first. Mason (1987) reviewed and compared systems for risk-rating stands for GM susceptibility.

Herrick (1982) used interactive multiple-variable screening procedure to assign mortality probabilities to individual trees using data collected in Pennsylvania. Numerous tree and stand variables were considered but only three variables, species, crown condition and aspect, were retained. The hazard rating system indicated oaks with poor crowns were most likely to sustain mortality when defoliated. The system was further refined, using data collected over 3 years (Herrick and Gansner 1986). Basal area of oaks and specific oak species, crown condition and stand diameter were retained in the revised hazard rating system. Gansner (1981) examined numerous variables to rate stand vulnerability in Pennsylvania using similar multiple-variable screening techniques. Critical variables retained in hazard prediction equations included number or percent of white oak trees and trees with poor crowns. Additional variables were required to predict tree mortality and timber value loss. Models developed by Gansner (1981) accounted for 73% of the variation in defoliation-induced mortality. Species, aspect, tree diameter, and site index were used to distinguish live trees from dead trees following GM defoliation in West Virginia and Maryland (Hicks 1984, Hicks and Fosbroke 1987).

Impact
Much information on GM impact and tree mortality was acquired from records at Melrose Highlands, MA, collected from 1911-1931 on 264 plots located along the seaboard of New England. Baker (1941) found preferred species sustained an average defoliation level of 37% from 1912-1921, with

30% cumulative mortality. Greatest mortality coincided with drought and Agrilus bilineatus activity. Campbell and Valentine (1972) reported variable mortality among species, with mortality rates ranging from 25% (red maple) to 58% (white oak). Activity of GM accelerated decline of pioneer species and altered species composition. Mortality was inversely related to tree vigor. Campbell and Sloan (1977) intensively analyzed the Melrose records. Selectivity of GM decreased as populations increased, and species not favored by GM were more likely to die after severe defoliation than oaks. Their findings indicated oak trees required 10 years to recover from a single, heavy defoliation. Heavy defoliation tended to reduce susceptibility of residual stands due to increased presence of non-favored species and resistant individual trees. In addition to mortality and growth loss, GM defoliation reduced quality of remaining trees due to crown dieback, epicormic branching and secondary infestation by wood-boring insects or pathogens.

Impact of GM defoliation on forest stands is highly variable and damage is seldom distributed uniformly among stands (Gansner 1981). Numerous factors including severity and duration of GM infestation, species composition and stand vigor interact to determine the amount of mortality and growth loss sustained. Although mortality varies considerably among stands, the presence of oaks is consistently associated with heavy defoliation and damage. However, vulnerability often varies among oak species. In Connecticut and Pennsylvania, trees in the white oak group tended to be most vulnerable (Stephens 1987, Gansner and Herrick 1982), while red oaks suffered greatest mortality in New Jersey (Statler and Serrao 1983). In one case, mortality of white oaks exceeded that of red oak from 1959-70, while the reverse was true from 1970-80 (Stephens 1987, Hicks and Fosbroke 1987). All oak species were heavily damaged during outbreaks in Pennsylvania (Quimby 1987). Wargo in Doane and McManus (1981) showed GM defoliation initiated a sequence of events that predisposed oaks and maple to invasion by secondary organisms (Armillaria mellea and Agrilus bilineatus) and subsequent mortality. In Pennsylvania, aspen sustained an 8% annual mortality rate, but represented less than 1% of the sampled trees (Herrick and Gansner 1987).

Impact of initial GM outbreaks in new environments tend to be more drastic than subsequent outbreaks (Campbell and Sloan 1977). Gansner and Herrick (1987) compared GM impact in New England, where GM has long been established, to impacts in Pennsylvania where infestation is much more recent. Inventories of federal land indicated the combined oak growing-stock volume in New England states had increased by 23% during 1980-84 from levels recorded in 1968-73. However, oak timber accounted for slightly less of the total hardwood inventory. Balance between growth and mortality was lower for oaks than other hardwood species, but was still positive. Observations in 1985 indicated little change in average stocking levels since 1979, although the oak component was reduced by 5%. Proportion of less-preferred species increased. Losses in volume and value of stands due to GM were nearly offset by increased growth rates, salvage of dead or dying

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trees and concentration of mortality on small or low-grade trees. Gansner and Herrick (1987) found impacts were more severe in Pennsylvania, at the leading edge of the infestation, following widespread defoliation from 1980-82. Cumulative mortality from 1979-84 varied greatly among plots but averaged 17% across all species. Overall mortality of aspen, northern red oak and white oak through 1984 was 42%, 14% and 23%, respectively. Two years of GM defoliation in newly infested stands in New Jersey drastically altered species composition (Kegg 1973). Oak density was reduced by 40% and mortality rates for oak species varied from 27-84%, compared to 6% mortality of non-preferred species (Kegg 1973). Significant mortality was associated with defoliation levels greater than 40% and sharp increases in mortality occurred 2 years after major defoliation.

Ability of trees to survive defoliation is directly related to tree vigor (Campbell and Sloan 1977). Quimby (1987) reported GM defoliation combined with 4 consecutive years of drought severely impacted forests on state land in Pennsylvania. Surveys of 690,300 ac indicated mortality rates of 28-51% for pulpwood and 32-51% for sawtimber. Total volume losses were estimated at 218 million ft^3 of pulpwood and 951 million bf of sawtimber. Total value lost was $104 million or $151/ac. Mortality was most severe on drought-stressed sites and on areas where intermediate or improvement cuts had occurred within the previous 5-6 years. Root compaction, Armillaria rot, Agrilus bilineatus and stress due to increased exposure may have increased vulnerability of the logged stands.

GM defoliation of conifers can occur in mixed wood stands, or when conifer stands, Christmas tree plantations, etc. are adjacent to infested hardwood stands. Stephens (1987) observed 35-40% mortality of hemlocks defoliated in a mixed wood stand. The long-term Melrose data set indicated 26% mortality of white pine over 20 years (Campbell and Valentine 1972). Young white pine losing 100% of the old foliage and 41-61, 61-80 and 81-100% of new foliage suffered 12, 11 and 32% mortality, respectively (Minott and Guild 1925). Defoliation exceeding 90% of white pine foliage caused 11, 16 and 42% mortality of dominant and codominant, intermediate and overtopped crown classes of trees (House 1963). When eastern hemlock was defoliated, 68, 92 and 42% of trees in the three crown classes died (House 1963). Mortality of conifers following GM defoliation in Connecticut was infrequent except when defoliation exceeded 90% (Stephens 1987). Dominant or codominant trees were less likely to die than suppressed or intermediate trees and mortality was lower in thinned stands than in unthinned stands. Growth rates were inversely related to defoliation and were reduced by 1-16 fold. Campbell and Garlo (1982) found little defoliation of pitch pine and suggested pines may gain a short-term advantage when oaks in mixed stands are defoliated.

Growth loss as a result of GM defoliation is generally not as well-documented as mortality. In general, growth reductions are roughly proportional to degree of defoliation (Minott and Guild 1925, Baker 1941).

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Kulman (1971) surveyed literature and reported average oak defoliation of 37% was associated with average growth reduction of 34%. In years of 100% defoliation, growth was reduced by 52%. Kulman (1971) cited studies that found one year of complete defoliation reduced diameter growth in white pine, eastern hemlock and oaks by 14, 40 and 24% the following year. Average yearly losses for the five-year postdefoliation years were 16, 28 and 7% for each species. Average growth loss of 38% was reported by Minott and Guild (1925). Growth reductions of 25-60% have been observed following defoliation of oaks (Baker 1941, Brown et al. 1979, Campbell and Garlo 1982). During years of defoliation, expected growth loss may range from 25-65% but long-term impacts of defoliation on growth are poorly understood (Hicks and Fosbroke 1987).

Regeneration capacity may be severely impacted as a result of lower seed production, loss of stump sprouting potential (due to mortality or low vigor), and mortality of advance regeneration (Gottschalk 1984). Ten years after GM defoliation in Pennsylvania, the understory was dominated by shrubs and ferns with little establishment of tree species (Gansner 1985). Defoliation of a oak overstory favored the existing red maple understory (Collins 1961). Establishment of commercial tree seedlings may be precluded by vigorous competition from understory species (Ehrenfeld 1980).

Large-scale GM defoliation can affect many attributes of forests other than mortality and growth loss. Corbett and Lynch (1987) found nutrient reallocation from vegetation to soils, water yields and density of fecal indicator organisms all increased when Pennsylvania watersheds were defoliated by GM. GM infestation may also affect wildlife, either directly via changes in food quality or indirectly via changes in habitat. Cooper et al. (1987) suggested GM larvae in sparse populations were primarily an incidental food for most birds, who generally dislike the hairy larvae. Outbreak GM populations may cause birds to vary feeding and foraging behavior. Fewer birds may forage in heavily defoliated areas, but most species are unlikely to completely vacate areas. Open-habitat birds may forage preferentially in defoliated areas. Changes in species composition resulting from GM management or defoliation may subsequently affect bird communities. Defoliation of oaks and subsequent reduction of mast crops (acorns) may impact squirrels and other animals (Goebl 1987).

Heavy defoliation of the Allegheny National Forest in Penn reduced recreational use by 20%, directly impacting government and private businesses and activities (Goebl 1987). Surveys indicated 26% of visitors shortened their visits due to effects of GM infestation. Negative impacts included reduced visual quality, unattractive leaf litter, loss of shade in developed recreational areas, falling larvae and frass, skin irritations and abundant Sarcophagid parasitoids.

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Management and Control

The ideal approach to GM management may fall into the concept of integrated pest management (IPM). The focus of IPM programs is the compatible utilization of available tools to manage populations at innocuous levels based on ecological and economical criteria (Reardon et al. 1987, Cameron 1991). A large-scale GM IPM program was implemented in Maryland and is described by Reardon et al. (1987); success of the project has not yet been determined. Various control methods including pesticides, NPV, pheromones, phytochemicals and sterile male release are reviewed in chapter 6, Doane and McManus (1981). A recent publication described IPM applications for GM (Anonymous 1990). Risk/hazard rating can be used to identify trees or stands likely to sustain an infestation or damage. Population monitoring using egg-mass surveys and detection using pheromone traps can be used to monitor GM distribution and population trends. Computerized expert systems are under development to relate GM impacts to management objectives. Ravlin (1991) discussed programs for GM monitoring and development of GM decision support systems. Biorational methods of pest control, including inundation of GM populations with sterile males, and introduction of sterile egg masses, are under development. Silvicultural treatments can reduce both susceptibility and vulnerability of stands and are discussed in detail below.

Foliage protection, and in some cases, population reduction may be obtained through insecticide application, and should be considered in IPM programs. Recent trends indicate an emphasis on microbial insecticides as opposed to chemical insecticides (Anonymous 1990). Bt is most widely applied, but recent improvements in Gypcheck (GM NPV) and research on microsporidia (Nosema sp) indicate other compounds may be available (Anonymous 1990). Most pesticides are applied to early instar larvae, when leaves are about 1/3 expanded (Gottschalk 1991). Decisions to apply pesticides are often based on a threshold level of 600 egg masses/ha or anticipated defoliation exceeding 60% (Campbell and Valentine 1972, Montgomery 1990). Above this level of defoliation, trees expend energy reserved to refoliate, reducing overall vigor (Montgomery 1990). Status and characteristics of microbial pesticides used on GM are discussed by McManus (1990).

Cameron (1991) evaluated IPM efforts with respect to GM. He concluded that with the possible exception of the Maryland project (Reardon et al. 1987, Reardon 1991), GM IPM has not been satisfactorily implemented. The large acreage involved, political constraints, a lack of reliable suppression tools and other factors were cited as contributing to the failure of GM IPM. Ravlin et al. (1987) recommended increased commitment to leadership and coordination among agencies at all levels of GM management. They also indicated a need for implementation of systems analysis, standard sampling protocols, computerized database management and spatial analysis, and transfer of technology for GM management.

Silvicultural treatment may offer the best chance of long-term mitigation of GM outbreak and damage. Silvicultural guidelines for GM management along the advancing front of the infestation were developed by Gottschalk (1987) in West Virginia and Quimby (1987) in Pennsylvania and are summarized below. Applicability to Minnesota forests is uncertain due to differences in forest types and management objectives. Silvicultural treatment to mitigate GM impact requires information and knowledge of stand and insect characteristics. Prescriptions will be determined by proximity of defoliation in time and space, coupled with economic considerations and stand attributes.

Gottschalk (1987) developed the following recommendations. Preventative action may be taken where defoliation is not expected within the next 5 years. Stand regeneration may be appropriate when stands are poorly stocked or are expected to be harvested within 5 years. A shorter rotation can assure regeneration through stump sprouting and seed production and avoids lost value in salvage sales. Presalvage harvest may be appropriate where advanced regeneration stocking and stump sprouting potential are adequate. When potential regeneration sources are not adequate and stand susceptibility and vulnerability are low, presalvage shelterwood cutting may be utilized. Where potential regeneration is low and susceptibility or vulnerability is high, sanitation conversion to nonpreferred species may be the only alternative.

Fully stocked stands, 6-15 years from harvest, may best be handled by deferring cutting for several years and re-examining status when defoliation is imminent. Stress from thinning or harvesting persist for 3-15 years after treatment. Stress coupled with defoliation may result in relatively high mortality. Valuable stands may require insecticide application if a GM outbreak is expected within the recovery period.

Sanitation thinning or presalvage thinning may be considered when stands are more than 16 years from maturity and have greater than 80% stand density. Sanitation thinning should reduce stand susceptibility by removing preferred hosts and refuges of GM and promoting predator and parasite habitat. This treatment is most appropriate where less than 50% of the basal area is in preferred species and where it doesn't conflict with other objectives. Presalvage thinning reduces vulnerability by early removal of trees likely to die if defoliated. This treatment is appropriate where more than 50% of the basal area is preferred hosts. Vulnerable trees may include trees with poor crowns, especially oaks, and trees with fair crowns on dry, poor sites.

When defoliation is occurring or expected within 5 years, stands should be examined and insecticide application may be required. Insecticide use requires consideration of stand age, condition and value, severity of the GM threat and management objectives.

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After defoliation has occurred, stands should be examined in 1-3 years to assess resulting mortality. Regeneration may be appropriate if damage is high and stocking poor or if stands will mature in 10 years. If regeneration is adequate, salvage harvests may be used. If regeneration stocking is inadequate, salvage shelterwood or conversion treatments can be used to obtain regeneration or convert to nonpreferred species. Stands with low to moderate damage, adequate stocking and more than 10 years from maturity can be thinned to salvage dead trees. Salvage cutting can be used if stocking is adequate but mortality exceeds 30%. Cutting in low to adequately stocked stands with less than 30% mortality should be deferred.

Quimby (1987) provided the following general recommendations for Pennsylvania oak forests.

Insecticide application to valuable stands on good sites, particularly those near harvest, should be considered when egg mass count exceeds 500 large, healthy egg masses/ac. Spray areas should be kept as small as possible to promote parasite build-up in untreated areas. Any spray decision must include the realization that spraying may need to be repeated at 2-3 year intervals indefinitely. Even with excellent spray coverage, a small percent of larvae will likely survive and destructive populations may rebuild. Low value stands and those on poor sites may be economically infeasible to treat unless they are high-use or recreational areas. These sites may serve as reservoirs of parasites. Mature oak stands scheduled for clearcutting should be harvested in advance of anticipated defoliation. Stump-sprouting will not occur if trees are killed by defoliation or secondary pests. Insecticide application may be required in stands scheduled for an intermediate harvest cut or thinning 5 years before or after defoliation. The combination of defoliation and intermediate cutting may cause heavy mortality. Salvage cuts and deferred intermediate cuts should be scheduled for 2 years after the collapse of an infestation, since mortality will continue to accrue over this period. Drought stressed, valuable stands with high egg mass counts should also be considered for insecticide treatment. Stands with an overstory of preferred species, and understory of conifer seedlings or saplings and high egg mass counts may require treatment to prevent mortality of conifers. Where compatible with other objectives, prescriptions and harvests should promote forest species diversity.

Gypsy moth status in the Lake States
Michigan: GM was first discovered in Michigan in the 1950s and thought to be eradicated following DDT and other insecticidal sprays in the 1970s (Dreistadt 1983). Driestadt (1983) suggested, however, that endemic populations may have been present for 30 years, regulated largely by environmental factors, and were eventually bolstered by carried-in gypsy moths. Gypsy moth populations began to build in the late 1970's. It should be noted that increased pheromone trap catches in Michigan coincided with a switch from Gyplure bait to Disparlure, which was much more effective.

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Frank Sapio, Michigan Department of Natural Resources, reported that aerial surveys of four counties were carried out in 1991 (pers. communication). Mortality in the four county area was observed on 30,000 ac and ground surveys of individual plots indicated mortality of 25-80% of stems. Trees that are dying are primarily northern pin oak. Mortality is most severe in open-grown stands on poor sites (SI 50-55) and where trees are generally overmature (90-100 years old). Some mortality also occurred where stands were thinned during the recent drought and/or where stands were defoliated during a concurrent outbreak of forest tent caterpillar. The thinned stands are composed mostly of high value oak. Salvage of dead oaks has been complicated by a lack of funding for replanting and by direction of resources towards a new outbreak of jack pine budworm. Preliminary spatial analysis of defoliation indicated a poor correlation with distribution of mortality and 1990 defoliation in three of the four counties. Mortality in these three counties may be primarily a result of drought stress and subsequent attack by two-lined chestnut borer and impacts of forest tent caterpillar defoliation. Permanent plots are currently being established to examine long-term impacts of GM defoliation at 3-10 year intervals.

According to 1991 Michigan Department of Agriculture (MDA) treatment summaries, three applications of Bt were applied to 160 ac for GM eradication. Two applications of Bt were made on over 200,000 ac for GM suppression. MDA personnel estimated 500,000 ac were defoliated 50% or more based on aerial surveys. About 140,000 more ac were defoliated in 1991 than in 1990. Male moths were captured in 80 out of 83 counties. Currently, 23 counties have quarantines restricting export of Christmas trees out of Michigan (1991 Michigan Legislative Tour report). Demand for information related to GM increased in all agencies by ca 500% from 1990 to 1991.

Witter et al. (1990) examined relations between GM success and forest site factors in Michigan. Results to-date indicate GM may be more successful on aspen than other species, and that phenological development varies among host species and may affect GM growth and survival.

Hart (1990) conducted a study in Michigan northern hardwood stands where aspen comprised ca 50% of the canopy. He found quaking aspen was preferred by GM over bigtooth aspen. Mean defoliation rates for the two species over three years were 35 and 21%, respectively. Mortality of quaking aspen over three years averaged 8% per year versus 2% per year for bigtooth aspen. Death was attributed to one nearly complete defoliation and subsequent presence of Armillaria. Hart (1990) could not determine if heavily defoliated aspen was more likely to be invaded by secondary organisms or if low vigor aspen was more likely to be heavily defoliated.

Hajek and Elkington (1990) reported that a fungal pathogen caused extensive mortality in GM larvae in 1989 in the northeastern U.S. It was identified as Entomophaga maimaiga, and caused 60-88% mortality on surveyed plots.

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The fungus was originally introduced from Japan as a potential biocontrol agent in 1910 and 1911 in Massachusetts, but was not detected or considered established. High incidence of this fungus was associated with abundant early summer rainfall. Research on E. maimaiga is in progress in Michigan and the northeastern U.S.

Wisconsin: High trap catches of GM were recorded in Wisconsin in 1991. Total catches were expected to be lower than the record 15,642 males captured in 1990 (Anonymous 1991). High trap catches, and females, egg masses and other evidence of infestation were found in 5 counties. Most moths were trapped in counties bordering Lake Michigan. One to three counties may be declared generally infested in 1992 (Steve Krause, WI Dept. Agric., Trade and Cons. Prot., pers. comm.). Eleven localized infestations were delineated in 1990 and scheduled for eradication by Bt application or mass density trapping in 1991 (Anonymous 1990).

Minnesota: Ascerno et al. (1984) described gypsy moth detection in Minnesota. Pheromone traps are the primary method used to detect and monitor GM populations. Traps are baited with a chemical replica of the female sex pheromone; male moths attracted to the pheromone are caught in the sticky interior of the trap. Single trap catches generally are not indicative of established populations. Multiple moth catches, particularly in the same area in consecutive years may indicate an infestation. When multiple moths are captured, trapping intensity may be increased the following year to delimit the infested area. These areas may also be surveyed for viable egg masses or pupae. Pheromone traps may also be used alone, or in combination with insecticide treatment to eradicate small, localized infestations.

The USDA Animal and Plant Health Inspection Service and the Minnesota Department of Agriculture are the primary agencies responsible for detection, survey and eradication of GM in Minnesota. When GM becomes established and is no longer a candidate for eradication, the Minnesota Department of Natural Resources (DNR) will be responsible for GM management on forested lands. The USDA Forest Service will assist the DNR in management of established GM infestations and will be responsible for operations on federal land.

GM was first collected in Minnesota in 1969, when egg masses and pupal cases were found in Duluth (Ascerno et al. 1984). In 1976, the first male moth was trapped in Hennepin county and 26 male moths were captured in 1980 in the Twin Cities.

A potentially important control factor in Minnesota may be mortality of overwintering eggs. Gypsy moth eggs are killed by exposure to cold winter temperatures. However, protection by snow cover or debris may insulate eggs from extreme cold. Sullivan and Wallace (1972) examined GM egg survival in Canada. With snow cover of 2, 4, 6 and 8 inches, 50% of eggs

survived exposure to -39, -44, -54 and -62° F, respectively. In addition, eggs from a Quebec population were more cold tolerant than eggs from a Massachusetts population, indicating strong selection for cold tolerance.

Georgeff (1989) used equations developed in other areas of the country (Gansner and Herrick 1984, Valentine and Houston 1984) to risk and hazard rate stands in southeastern Minnesota. The study was limited to stands in two townships in Winona county, in the Richard J. Dorer Memorial Hardwood Forest. Fifty-60% of acreage in the Dorer forest is classified as oak-hickory, with very little hickory present. About 80% of oaks are red oak, with white, bur and black oak comprising the remaining 20%. Other common species included basswood, aspen, birch, elm, sugar maple and ash, a non-preferred species. Only 3 of 51 sampled stands received high risk ratings. Susceptible stands were characterized by dense, small diameter trees, a variety of preferred species and a southern or western aspect. Stands dominated by red oak, with large diameter trees tended to receive low risk ratings. Hazard rating indicated forests in the two townships may be quite vulnerable; 36 of 51 stands received high hazard scores. Poor crown condition, indicative of low vigor, was the primary attribute typifying vulnerable stands. However, the author questioned the accuracy of his crown condition determination. Stands with southerly aspects were also likely to be more vulnerable.

An anticipatory biocontrol experiment is also currently in progress in Minnesota. An exotic parasite, _Coccygomimus disparis_ was thoroughly evaluated and released in 1990 with the goal of establishing endemic populations on native Lepidopteran defoliators. The objective of the program is to augment the existing parasite complex prior to GM establishment, to dampen the explosive population surge characteristic of newly established infestations.

A.1.5
Two-lined Chestnut Borer - _Angrilus bilineatus_ (Weber)

Two-lined chestnut borer (TLCB) is a native, wood-boring insect that attacks stressed and weakened oaks. Red oak is the preferred host of TLCB, but all Minnesota oak species are attacked. Under normal circumstances, attack by TLCB is confined to low-vigor trees and broken branches. However, periods of drought or other stress predisposes trees to attack by TLCB. Damage to the inner bark of branches and stems leads to dieback and eventual mortality. Widespread outbreaks of TLCB have occurred where drought, defoliation, ice-storm damage or man-made disturbances were severe (Haack and Benjamin 1982, Minnesota Dept. Natural Resources 1991).

Life History
Emergence of adult two-lined chestnut borers (TLCB) occurs from late May through mid-September, but peaks in mid-June (Haack and Benjamin 1982).

Adults live ca 28 days and feed on hardwood foliage before mating and laying eggs. Oak foliage was significantly preferred by adult TLCB to foliage from aspen, hickory, black cherry and basswood in a bioassay test (Haack and Benjamin 1982). Among oak species, adult TLCB in Connecticut preferred scarlet oak, followed by chestnut, white, black and red oak (Dunbar and Stephens 1976). Adult female beetles are attracted to ethanol and other volatiles of stressed oaks for oviposition; females will not oviposit on either healthy or dead trees (Dunn et al. 1986). One to seven eggs are laid on bark, usually in areas exposed to sunlight. Eggs hatch in 7-14 days.

Larvae feed on cambium from late June through August, completing 4 instars (Haack and Benjamin 1982). Meandering galleries constructed by feeding larvae will eventually girdle branches, causing leaves to turn brown. Haack et al. (1983) examined the successional pattern of borer infestation in declining oaks in Wisconsin. Weakened oaks were generally attacked first by TLCB, then by various species of Buprestid, Cerambycid and Scolytid beetles as trees died and wood dried out. Parasitism of TLCB larvae by a Chalcid was described by Haack et al. (1981). An average of 10.5% of TLCB larvae in Wisconsin were parasitized by the Chalcid. Ultimate instar larvae overwinter in pupal cells in the bark or sapwood. Pupation occurs in spring.

Impact
TLCB attacks the inner bark of branches, causing dieback. Flagging becomes fully evident in August-September after larvae complete development. Brown leaves usually remain attached to trees, even after normal leaf drop in autumn (Anonymous 1991). Infestation and damage by TLCB proceeds from the top of the tree down, and eventually the stem may be girdled. During a severe drought, trees may die within one year, but mortality usually occurs over 2-4 years. Foliage of infested oaks is typically discolored, small and sparse (Anonymous 1991). Diagnostic signs of TLCB include larval galleries engraved in cambium and sapwood, D-shaped exit holes of adults and flagging caused by dead branches. Symptoms used to distinguish TLCB damage from oak wilt and anthracnose are described in a recent publication from the Minnesota Dept. Natural Resources (Anonymous 1991).

High mortality from TLCB was observed in Minnesota following severe drought in 1988, and was reported in the 1988-89 Minnesota DNR Annual Insect and Disease Report. Oak mortality ranged from 1-20% in 1988 and reached 70% in some stands in central Minnesota in 1989. Stands previously defoliated by forest tent caterpillar sustained highest mortality. High mortality rates were also associated with stands growing on poor, droughty sites, stands with a history of grazing and with occurrence of Armillarea infection. Trees along logging roads and edges of clearcuts generally died first.

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Contributing Factors

Significant impact from TLCB occurs only when trees are severely stressed from drought or other agents. In the absence of drought or severe stress, TLCB populations are endemic and infestations are patchy and scattered throughout oak stands. Damage is typically limited to branches and occasional trees (Dunn et al. 1986, Anonymous 1991). Drought and other forms of stress disrupt photosynthesis and many growth-related processes in trees, reducing energy reserves and tree vigor. Root starch levels of TLCB hosts have been used as an index of host vigor (Wargo 1975). Starch leveis of infested trees are typically low or depleted (Haack and Benjamin 1982). Not only do stressed trees have fewer resources to resist TLCB attack, they are also more likely to be located by TLCB adults. Stressed trees release volatiles attractive to TLCB females, who subsequently oviposit on these hosts (Dunn et al. 1986). Trees adjacent to stressed oaks are more likely to be infested than distant trees, sometimes resulting in pockets of dead and dying oaks (Haack and Benjamin 1982). Although drought is the most notable stress, mortality from TLCB has also occurred in association with defoliation by other insects, damage from livestock grazing, severe wounding, and Armillarea root rot (Anonymous 1991).

Management and Control

Because TLCB outbreaks are so closely related to tree stress, maintenance of tree vigor should be the primary management goal. Stocking levels can be adjusted to reduce competition in stands and promote optimal growing conditions (Gingrich 1971, Anonymous 1991). Thinning, however, should be avoided during a TLCB outbreak, particularly when trees are drought-stressed. Thinning will initially open stands to drying winds, may increase soil temperature, and can compact soil or damage roots (Anon. 1991). Fresh stumps may increase Armillarea presence. Thinning should be delayed for ca five years after drought and no more than 30% of the basal area should be removed in one operation (Anonymous 1991).

When TLCB outbreaks occur, management options may be limited to sanitation, salvage or delay of any activity in the stand. Sanitation may be the best alternative when infestation is a result of storm damage, wounding or other localized events. Sanitation harvests should be directed at reducing TLCB populations before additional trees are infested. Sanitation is most appropriate when the ground is frozen and possibility of wounds to residual trees is minimal. Dead trees and trees with greater than 50% dieback should be removed the following winter.

When TLCB outbreaks are widespread as a result of drought, sanitation harvests will be inadequate. Sanitation harvests are unlikely to reduce TLCB populations or remove enough infested oak to prevent attack of residual trees. In these situations, management activities within stands should cease until trees recover some vigor, to avoid wounds or further disturbance. Severe drought stress can reduce vigor for up to 5 years.

Salvage of dead and dying trees can reduce economic impact of TLCB outbreaks by recovering timber prior to degradation. Salvage will likely have minimal effect on TLCB populations and should only be considered where economically justifiable. Trees should be marked for salvage prior to leaf drop in autumn. Care should be taken to avoid wounds or further stress of residual trees.

Stump-sprouting will be limited in TLCB infested stands. Oak regeneration in such stands must occur through advance regeneration, rather than from stump-sprouting.

Other options for TLCB control may be appropriate in some situations. Trap trees, preferably trees already infested or intended for removal, can be girdled in spring to attract adults. Adults will oviposit on the trees, but girdled trees will die and desiccate too quickly for larvae to survive. Similarly, infested oaks that are felled in summer will dry rapidly, resulting in larval mortality. It may be beneficial to favor woodpeckers that feed on overwintering larvae. Chemical pesticides to control TLCB should be applied only to high-value urban or ornamental trees. Chemical or microbial insecticides applied during outbreaks of defoliators such as forest tent caterpillar may protect trees from subsequent TLCB attack (Gass and Luley 1990).

A.1.6
Pear Thrips - Taeniothrips inconsequens (Uzel)

Pear thrips, a native of Europe, was detected in California and later found on the East Coast (Stannard 1968, Palm 1985). Currently, pear thrips is considered to be distributed throughout Canada and the northern United States, south to Virginia and in California. Until recently, pear thrips was known as a pest of pome fruit trees on the West and East Coasts. In 1979, however, severe defoliation of sugar maple was observed in Pennsylvania; the causal organism was later identified as pear thrips (Anonymous 1987). A widespread and severe outbreak of pear thrips on sugar maple in Pennsylvania and New England occurred in 1988, focusing attention of forest specialists on this insect. In 1990, a survey for pear thrips was conducted in the northeastern U.S. (Hollingsworth et al. 1990). Minnesota was not included in the survey. However, low numbers of pear thrips were detected in Wisconsin, although no defoliation was noted.

In 1991, five sites across 3 counties in Minnesota (Hennepin, Chisago and Isanti) were surveyed for pear thrips (Bruce Potter, MN Dept. of Agric., pers. comm.). To-date, traps from four of the five sites have been examined; pear thrips were detected in all cases. Pear thrips can, therefore, be considered established in Minnesota. Observations from northeastern states indicate pear thrips populations and damage vary widely from year to year. Severe and widespread damage, such as that observed in Pennsylvania and New England in 1988 apparently occurs only when a number of

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environmental and other conditions coincide (Bruce Potter, MN Dept. Agric., pers. comm.). We may observe sporadic outbreak populations in Minnesota when conditions are appropriate, but predictions are difficult due to our limited knowledge. Detection surveys are expected to continue in Minnesota (Bruce Potter, pers. comm.).

Life History
Biology and life history information was derived from Lewis (1973), Palm (1985), Anonymous (1987), Parker et al. (1988). Detailed life history studies in Vermont are ongoing (Skinner et al. 1991). Adult emergence occurs in spring, prior to budbreak, and appears to correspond to soil temperatures of 40-50 °F. Adults feed in buds, rasping tissue and sucking sap. Pear thrips are parthenogenic and females lay an average of 130 eggs. Eggs are laid on petioles and along midveins of leaves. Adults are present until leaves are 1/4 to 1/2 expanded. Larvae hatch in 5-17 days, when leaves are about 1/3 expanded. Larvae are active, but little movement occurs among leaf clusters. Larvae feed 2-3 weeks, then migrate to the ground. Pupation occurs in the soil. Adults are present in December, but do not leave the soil until the following April or May. Pear thrips are believed to have one generation per year. Weather conditions are thought to be related to outbreaks of thrips, but few data are available (Houston et al. 1988).

Forest species that may be attacked by pear thrips include sugar and red maple, basswood, birch, beech, ash and black cherry (Simons 1985). Laudermilch (1988) observed minimal effect of thrips feeding on red maple in Pennsylvania. In a few cases, thrips feeding apparently caused black cherry to abort leaves. Only sugar maple has been severely affected by pear thrips as yet.

Impact
Sugar maple foliage damaged by thrips may be stunted or dwarfed, mottled yellow to green-brown and crinkled or distorted. Crowns of attacked trees may appear thin or ragged and injury may resemble frost damage. Moderate damage may result in premature leaf drop. Severe feeding damage can result in complete defoliation (Parker et al. 1991). Sugar maple seedlings were exposed to adult thrips at different stages of bud burst (Kolb and Teulon 1991). Symptoms of thrips damage included reduced leaf area (up to 34%), reduced leaf size, and chlorosis, tattering and cupping of leaves.

Severe damage in Pennsylvania occurred on 50,000 to 100,000 ac from 1985-1987. Outbreak populations combined with more intensive sampling efforts in 1988 indicated over one million ac of severe damage (Burns 1988). Laudermilch (1988) indicated pear thrips is currently the most serious threat to the existence of sugar maple in Pennsylvania, most of which occurs in mixed hardwood stands. Surveys in 1987 found heavy damage on 100,000 ac in Vermont and Massachusetts (Burns 1988). Burns (1988) suggested damage was spreading to the Canadian border. Pear thrips has apparently been observed in Quebec, but no severe defoliation has been recorded

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(Parker et al. 1988). Recent data indicates pear thrips populations in the northeast declined dramatically from 1990 to 1991 (Anonymous 1991).

Effects of thrips damage on growth and mortality of sugar maple are poorly known. Laudermilch (1988) could not show evidence of thrips-induced mortality in an area in Pennsylvania that had been infested for 9 consecutive years. Houston et al. (1988) indicated trees with complete defoliation may have dieback ranging from a few inches to several feet. Growth loss and impact of thrips on sap production have not been quantified. Observations indicate that thrips propensity for feeding in flower buds may significantly impair seed production and sugar maple regeneration (Laudermilch 1988).

Contributing Factors
Damage by thrips may be highly variable among trees within a stand, among stands and among years (Kelley 1988, Burns 1988). Observation and anecdotal evidence suggest thrips may preferentially attack largest trees or "sweet" trees in stands (Kelley 1988). Apparent discrimination by thrips may also be related to phenology of budbreak, with trees most in synchrony with adult emergence being most heavily attacked. A common garden experiment with sugar maple seedlings indicated that amount leaf area reduction and damage depended on bud phenology at the time of thrips infestation, and varied among families (Kolb and Teulon 1991). Thrips may also prefer flowering trees; expansion of flower buds may occur slightly ahead of vegetative buds (Kelley 1988, Laudermilch 1988). Aerial observations of thrip damage in Vermont indicated trees on ridge tops, trees at higher elevations and trees on east-facing slopes (where sugar maple tended to be more productive) sustained greatest damage (Burns 1988). Thrips injury in conjunction with drought stress or Armillarea may increase negative impacts (Houston 1988). Trees in recently thinned stands may also be more vulnerable to thrip damage, presumably due to increased desiccation and drought stress (Burns 1988, Houston et al. 1988).

Management and Control
Stress or wounds to heavily defoliated trees should be avoided. Thinning may increase growth and productivity of young sugar maples, but may exacerbate thrip problems, presumably due to increased water stress (Houston et al. 1988, Hedberg 1988). Fertilization in concert with thinning may increase productivity, but may increase susceptibility to thrips (Houston et al. 1988, Hedberg 1988). Contact insecticides are currently registered for use on thrips (Laudermilch 1988). Chemical control may not be effective, however, since thrips are rarely exposed on the leaf surface. Natural enemies and weather may be involved in regulation of pear thrips populations (Anonymous 1987). Little is currently known about biocontrol organisms, especially in forest situations (Laudermilch 1988). Mills (1991) suggested synchronized univoltine parasites and fungal pathogens from Europe may hold promise for pear thrips control.

A.1.7
BASSWOOD THRIPS - Thrips calcaratus Uzel

Defoliation of basswood by basswood thrips (BT) has probably occurred since about 1979, but was originally attributed to frost damage. BT is an introduced species, first recorded in North America in 1925, and identified as the causal agent of basswood defoliation in 1988. Biology and impact of BT was described by Raffa and Hall (1988) and Raffa (1991), who conducted studies in Wisconsin. The information below is extracted from these reports. BT is distributed throughout the Lake States, the Mid-Atlantic states, Ontario and Quebec. The insect is thought to be univoltine, but little is known about its life history. In Europe, only Tilia spp. (basswood) are attacked. In North America, BT has been observed on hardwoods associated with basswood such as maple, hickory, beech, ash and oak, but these may be casual associations.

Life History
Adult BT overwinter in soil and emerge in early May, coincident with basswood bud swelling. Emergence may be temperature-related and is regionally synchronous. Adults feed in opening buds. Symptoms of feeding include shredded leaves, which eventually become chlorotic and drop if feeding is extensive. Adult feeding is probably the main source of injury, since most defoliation occurs before larvae are present. Oviposition occurs on the main veins of the lower leaf surface. Larvae appear in early June, complete development in June, drop to the ground and burrow into the soil. Development into the adult stage is usually complete by mid-July.

Impact
The outbreak of BT originated in northeastern Wisconsin and progressed throughout the Lake States. Currently, around 200,000 ac in Wisconsin and 100,000 ac in Minnesota are affected, with additional losses in Michigan. Seventy-seven trees were sampled in Wisconsin in 1988. These data indicated BT defoliation exceeding 30% reduced radial growth of basswood. Branch dieback has been observed. Refoliated trees often produce small, chlorotic or scorched leaves. The actual source of injury, however, is unknown. The extent to which trees other than basswood are threatened is unknown, but damage in the Lake States is so far limited to basswood.

Management and Control
Fundamental information must be acquired before management strategies can be developed. Two biological features of BT merit consideration. The nature of the BT outbreak suggests this introduced species has possibly escaped from natural enemies or pathogens that controlled populations in Europe. Opportunities for classical biocontrol (identification and importation of natural enemies) may exist, if native beneficial species are not impacted. Secondly, American basswood may be more sensitive to BT feeding than European basswood species. Ornamental basswood derived from European

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stock may be resistant to or tolerate BT feeding, although site or other differences cannot be eliminated.

A.1.8
Fall Defoliator Complex

The fall defoliator complex refers to various Lepidopteran species that occasionally cause heavy defoliation in mid- to late summer. Species preferred by these defoliators in Minnesota include oaks, basswood, elm, ash, birch, and aspen. The Minnesota fall defoliator complex commonly consists of variable oakleaf caterpillar (Heterocampa manteo Dbldy.), redhumped oakworm (Symmerista conicosta Franclemont), and orange-striped oakworm (Anisota senatoria Smith). Other Lepidopteran species and other insects, including walkingsticks, are occasionally included in the complex. Adults of fall defoliator species are typically present in June-July and oviposit on undersides of foliage. Larvae feed, often gregariously, for several weeks from July to August or September. Larvae drop to the soil to overwinter as pupae or as prepupal larvae in cocoons (Anonymous 1980, Solomon et al. 1980, Drooz 1984). Lawson et al. (1982, 1984) studied feeding and growth efficiency of A. senatoria. Growth and development of A. senatoria was influenced primarily by leaf nitrogen concentration and larval consumption rate (Lawson et al. 1982, 1984). Low growth rates relative to early season herbivores resulted from increased feeding efficiency; growth was not affected by leaf moisture or tannin concentration.

Epidemic populations of fall defoliators build periodically in Minnesota, usually persisting one to three years. Defoliation may occasionally be heavy. However, because defoliation occurs late in the season, just prior to leaf drop, impacts are seldom severe. Pathogens, predators and egg parasites generally build up rapidly and cause outbreaks to decline within three to five years. A recent outbreak in Minnesota persisted three years before natural enemies caused drastic population declines. Tree mortality is typically observed only if trees are severely defoliated for three consecutive years or if drought or secondary pests such as two-lined chestnut borer or Armillarea weaken trees. However, late instar larvae may wander searching for food when foliage availability is low. Invasion of homes, tents and cabins by caterpillars, abundant frass and loss of visual aesthetics can be a nuisance and may adversely affect tourist and resort business (Coulson and Witter 1984, Minnesota DNR Ann. Ins. and Dis. Rep. 1983). Potential interactions between early season defoliators (e.g. forest tent caterpillar or gypsy moth) and the fall defoliator complex are not understood.

A.1.9
Spruce Budworm - Choristonerua fumiferana (Clemens)

Spruce budworm (SBW) is widely distributed throughout eastern Canada and the northeastern U.S., and is the most destructive forest insect in North America. Due to its economic importance, this pest has been the focus of

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intensive research in both countries. In 1977, the Canada-United States Spruce Budworms project (CANUSA), a 6-year program of research, development and application, was initiated. A multitude of published materials related to SBW are available. This report utilized summary publications such as Managing the Spruce Budworm in Eastern North America (Schmitt et al. 1984) and Recent Advances in Spruce Budworms Research (Sanders et al. 1985). Original literature and government agency reports were also surveyed. Particular attention was paid to those references addressing SBW in Minnesota.

Life cycle
Primary hosts of the SBW are balsam fir, white spruce and red spruce. Black spruce, tamarack, eastern hemlock and white pine are occasionally attacked. SBW is a univoltine insect. Eggs are laid in July in masses of 20-60 eggs, often on the underside of needles. Hatching is generally complete by mid-August. First-instar larvae are photo-positive and move to branch tips. Larvae often spin down on silken threads and can be dispersed by wind currents. Larvae spin silken hibernaculae on bark or protected places, molt to the second instar and overwinter. Larvae emerge from hibernaculae the following April or May and again move towards branch tips. Larvae silk down in search of suitable feeding sites and may again be dispersed on wind currents. The two dispersal periods account for 60-70% of early instar mortality (Miller 1958). Larvae establish feeding sites on suitable hosts. Larvae typically mine one-year old needles, but will feed preferentially on staminate flowers of balsam fir when present or occasionally mine expanding buds. Third instar larvae emerge from needle mines; feeding thereafter is concentrated on the expanding foliage. Late-instar larvae are present from June through July; most foliage is consumed during the sixth (ultimate) instar. Two or more shoots may be webbed together to form feeding shelters. Clipped and webbed needles result in a reddish appearance of recently defoliated trees. During outbreaks, late larvae may be forced to backfeed on old foliage. Backfeeding can decrease subsequent fecundity. Pupation begins in late June and may last 8-12 days. Moths are generally nonfeeding, although female fecundity is enhanced by nectar or water sipping (Miller 1987). Males are attracted to females by a sex pheromone. After mating, females deposit most of their eggs before flying. Adult moths may be transported great distances (up to 370 miles) by winds and storm fronts, potentially introducing SBW into uninfested areas (Dobesberger et al. 1983 in Blais).

Population dynamics
Outbreaks of SBW are part of the dynamics of forests where balsam fir is an important constituent (Blais 1985). Endemic budworm populations tend to be very low (Greenbank 1963). Populations may fluctuate dramatically, often building rapidly over large areas. Outbreaks usually last for 7-10 or more years and may cover vast geographic areas. Brown (1970) illustrated the range of SBW outbreaks in Canada from 1909-1966. SBW defoliation in Minnesota from 1954-77 was mapped by Erickson and Hastings (1977).

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Quantity and quality of host foliage may affect population dynamics. Both nutritional and allelochemical factors have been related to survival, development and fecundity of SBW (Shaw and Little 1977, Mattson et al. 1983, Schmitt et al. 1983). Nitrogen may be especially important to budworms because of unusually low levels of foliar nitrogen in host species (typically below 1.5%) (Montgomery 1983). Reduced food supply is typically responsible for collapse of SBW outbreaks (Blais 1985). Climatic factors may also affect SBW. Late larval survival, for example, is favored by warm, dry weather. Phenological synchrony between bud burst and SBW emergence in the spring may affect early larval survival and host selection. Buds of balsam fir and white spruce typically open earlier than those of other host species and may be more accessible to early larvae.

Natural enemies may exert considerable control over sparse SBW populations, but are generally ineffective during epidemics (Neilson 1963). Several bird species regularly feed on SBW larvae (Morris et al. 1958, Crawford et al. 1983). Initial expansion of SBW populations may attract more birds and bird species. Invertebrate predators, especially spiders and ants, may prey on budworms (Campbell 1985). Other insects and mites also attack specific stages of SBW. Numerous parasites attack SBW, but only 13 species are common (Blais 1985). Parasitism is thought to be an important mortality factor in endemic SBW populations, although little information is available. Two species, Glypta fumiferana and Apantales fumiferana, have life cycles synchronized with SBW, but together usually kill less than 20% of SBW larvae during outbreaks (Blais 1985). Other parasitic species require alternate hosts, limiting their functional or numerical response to SBW population build-up (Blais 1985). Although parasites are generally unable to respond effectively to increasing SBW populations, they may speed up population collapse. Introductions of exotic and domestic parasites have not proved successful. Royama (1984) theorized a basic 35-year oscillation of SBW outbreaks regulated by combined actions of parasites and other biocontrol agents, plus an unknown "fifth agent," which may include pathogenic organisms. A variety of pathogens attack SBW, but rarely cause high mortality (Neilson 1963). Occasionally, weather conditions permit rapid build-up of specific pathogens and high late-larval mortality may occur over large regions. Sublethal infections may decrease vigor, fecundity and longevity of budworms. However, specific weather requirements and the solitary feeding habit of larvae may limit the overall effectiveness of pathogens.

Impact
Although impact of SBW depends on factors such as size and duration of the outbreak, stand composition and tree vigor, it is recognized as the most destructive forest pest of spruce-fir forests. During the 1910-1920 SBW outbreak in eastern Canada, 200 million cords of wood were killed (Swaine and Craighead 1924). Annual volume depletion from 1978-82 during a recent outbreak in eastern Canada was ca 1.5 billion ft^3. This amount is

equivalent to about one-half of the annual allowable cut of softwoods in eastern Canada (Witter et al. 1984).

Balsam fir is more vulnerable to SBW damage than other host species. Lower vulnerability of spruces is due to production of more shoots and foliage and lack of phenological synchrony with budworm feeding (Blum and MacLean 1985). In the Lake States, top-kill of balsam fir may begin after 2-3 years of heavy defoliation. Tree mortality may begin after 3-5 years, depending on tree vigor (Flexner et al. 1983). Immature stands may sustain 7-8 years of defoliation before mortality begins (MacLean 1980). Mortality ceases about 12 years after the start of an outbreak. Mature balsam fir may sustain 70-100% mortality and immature stands may sustain 30-70%. Mortality in spruce stands ranged from 36% in mature stands to 13% in immature stands (MacLean 1980). Spruce mortality may increase as proportion of balsam fir increases (Osawa et al 1986).

A hypothetical succession of events generally associated with defoliation of balsam fir was described by Montgomery et al. (1982) and Witter et al. (1984). After one year of severe defoliation (> 75% foliage lost), radial growth decreased by 20% and flowers and cone crops died. Two-three years of severe defoliation decreased radial growth by 30-50%, caused height growth to cease, and caused small roots and some treetops to die. After 4-6 years, tree growth nearly ceased, and mortality of suppressed, understory and mature to overmature trees began. Top-kill also increased, decreasing average tree heights by 1-12 feet and affecting up to 50% of stems. Top-killing not only decreases tree volume directly, but often results in stem deformities and sweeps (Raske 1981) and may provide an entry for decay fungi (Stilwell 1956). After 7-15 years, SBW populations began to collapse. Tree mortality continued, however, and included seedlings and saplings. Dead trees began to deteriorate due to secondary insect attack, pathogens and wind breakage.

Other workers have documented severe mortality and growth loss resulting from SBW outbreaks. Archambault (1983) showed severity and duration of defoliation significantly affected growth loss. Generally, balsam fir growth is reduced 15-20% in the first year of severe defoliation, 25-56% the second year and 75-90% in succeeding years (Batzer 1973b, Baskerville and MacLean 1979, Piene 1980). Kleinschmidt et al. (1980) found spruce-fir stands in Maine suffered 40-60% growth loss after 5 years of heavy defoliation. However, stands that were lightly defoliated sustained negligible loss in growth. MacLean (1980) reviewed available literature and concluded mortality in mature fir stands may approach 100%. Seymour (1985) reviewed methods of forecasting yield of budworm infested forests. Measurement of over 400 plots in Maine indicated 35% loss in yield over 5 years due to budworm defoliation (Brann et al. 1983 cited in MacLean 1985). Fir stands in New Brunswick were monitored for 20 years after collapse of a SBW outbreak (Baskerville and MacLean 1979). Total volume loss during the outbreak ranged from 18-80%. Only one of ten plots

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regained predefoliation volume, even though surviving trees increased growth rates. Stand projections over 75 years indicated that SBW-caused mortality and defoliation would ultimately reduce volume by nearly 50%. Baskerville and MacLean (1979) observed tree height growth reduction of 12-15%; height loss was more severe in immature than in mature stands. Regional losses during SBW outbreaks have also been reported by numerous other investigators (Turner 1952, Elliott 1960, Blais 1964a, 1981a, Mog et al. 1982, Howse et al. 1982, Kucera and Taylor 1983). MacLean (1985) presented a table summarizing studies on growth and yield loss incurred during SBW outbreaks.

Impact of SBW outbreaks in Minnesota have been severe. Montgomery et al. (1982) calculated 67% mortality of balsam fir volume in Minnesota during a SBW outbreak from 1912-early 1920's. Growth loss of 25% in the second year and 80% in the sixth year were sustained by balsam fir during a recent outbreak in Minnesota (Batzer 1973). Height growth of trees was reduced by 62%. Mortality and growth loss reduced stand yield by 67%; 60% of the loss occurred in 5 years after collapse of the outbreak. Net mortality amounted to 56% of balsam fir, and 33% of white and black spruce. Annual reports of the Minnesota Department of Natural Resources indicate populations were fairly low in 1978, but began building in 1979. By 1982, moderate-severe defoliation was observed on 95,000 ac. A loss assessment survey was conducted on 84 townships to evaluate impacts from 1977-1982. Volume losses were estimated to be 24% of growing stock and mortality was much greater in stands with a heavy balsam fir component. Defoliation continued to grow and peaked at 440,000 ac in 1986-1987. Extensive top-kill and mortality were observed where defoliation occurred for 3-4 consecutive years. Spring frosts in 1987 killed new balsam fir shoots and also adversely affected larval survival. By 1989, defoliation was down to 140,000 ac and balsam fir mortality was widely observed. Tree mortality 5 years after initial SBW attack was positively related to amount of basal area occupied by balsam fir (Batzer and Hastings 1981).

Production of cone and seeds is severely reduced during SBW outbreaks (Ghent et al. 1957, Hudak and Raske 1981). Young SBW larvae feed on flowers and older larvae may feed on cones, resulting in direct loss of reproductive structures (Powell 1973). Severe defoliation of balsam fir reduces flower production by 50% after one year and 75% after two or more years (Schooley 1978). Virtually all flowers are destroyed on black spruce, even by small budworm populations, due to high larval preference for flowers over foliage (Schooley 1980). Defoliation and resultant loss in tree vigor decreases tree reserves and indirectly reduces flowering.

High mortality of small roots (< 0.1 in diameter) is observed in balsam fir when severe defoliation occurs (Witter et al. 1984). Young, vigorous trees may be more able to regenerate new roots than mature trees. Balsam fir roots appear to die and recover faster than spruce roots. Dead roots may provide entry for decay fungi including Armillarea and butt rots. Armillarea

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fungi were present in 31-42% of trees examined in northwest Ontario after SBW defoliation (Witter et al. 1984). In New Brunswick, 65% of dead trees and 55% of live trees had Armillarea after 8 years of heavy SBW defoliation (Ostaff 1983).

Stress and decreased vigor associated with SBW defoliation can predispose trees to attack by secondary insects and pathogens (Basham and Belyea 1960). In Nova Scotia and Quebec, spruce beetles caused mortality to 25 and 35% of SBW infested stands, respectively (Blais 1985). Salvage of trees may reduce economic losses following SBW epidemics. However, yield and quality of pulp and paper produced from budworm-killed trees can be affected by invasion of secondary insects and pathogens (Sinclair, 1985 Basham 1986). Heavy slabbing and trimming may be needed in lumber processing, decreasing volume. Broken stems, resulting from sharp declines in sapwood moisture in defoliated trees, may be frequent during mechanical harvest. Broken stems may affect harvest volume and transportation costs (Witter et al 1984).

In most cases, SBW outbreaks do not dramatically alter species composition (Blais 1985), although trends may vary among regions (Ghent et al. 1957). Advance regeneration of fir is common in mature fir stands. Generally, seedling mortality is less than mortality of mature trees. Mortality of overstory trees following defoliation recycles stands to a younger age structure, setting the stage for another outbreak when regenerating trees mature (MacLean 1985). In Minnesota, 24 spruce-fir stands were re-examined 15 years after a severe SBW outbreak (Batzer and Popp 1985). Overstory composition had changed from 79 to 33% basal area in host species. Minimally acceptable stocking of balsam fir was present in the understory of two-thirds of the stands. White spruce seedlings were present in 66% of the stands, but densities were low. Studies in other regions have indicated a successional sequence of fir replacing fir after outbreaks (Baskerville 1975, MacLean 1984).

Historically, SBW outbreaks have often been followed by severe fires. Budworm damage combined with increased breakage and windthrow in defoliated stands increases fuel loading and subsequent fire intensity. Spring fires in budworm-killed balsam fir stands in Ontario behaved explosively (Stocks 1985). Forest fire potential is greatest 5-8 years after tree mortality occurs.

Contributing Factors
Potential for damaging outbreaks of SBW depends primarily on species composition and age of stands. Balsam fir is most vulnerable to SBW damage, followed by white spruce, red spruce and black spruce (Blum and Maclean 1985). Relative resistance of black and red spruce is due to greater production of shoots and foliage and lack of phenological synchrony between bud break and larval emergence in spring. Stands with large components of balsam fir generally have greater potential for mortality than stands

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dominated by spruce or hardwoods. MacLean (1980) showed percent mortality was positively related to basal area of balsam fir, particularly in mature stands (> 60 years old). In Maine, 10 years after an outbreak began, mortality rates were 77% for fir and 27% for spruce, even though fir comprised only 11% of total stem volume (Osawa et al 1986). However, amount of spruce and fir mortality was generally not affected by presence of nonhost species in Maine (Osawa et al. 1986).

Many authors have observed positive associations between stand vulnerability and amount of mature or overmature fir. High SBW populations may be associated with mature to overmature trees due to increased staminate flower production, reduced larval dispersal losses or more favorable microclimate (Blais 1952, Greenbank 1963b in Blais 1985). Mortality rates in mature or overmature stands dominated by fir ranged from 70-100% (MacLean 1980). Mortality in immature stands was variable but generally less, ranging from 30-70%.

Density and stand structure also affect mortality. Typically high basal area of balsam fir, red spruce and white spruce increases vulnerability. High vulnerability in dense stands may be related to lower tree vigor and poorly developed foliage or to decreased larval mortality during dispersal (Blum and MacLean 1984). Dominant or co-dominant host trees are usually less vulnerable than host trees in subordinate crown position (Blais 1958). Understory spruce and fir growing below a hardwood overstory are less exposed to SBW damage. Open stands with spike tops of host trees protruding from the canopy tend to be heavily damaged (Witter et al. 1984).

Various factors related to physiography, soil and vegetation affect distribution of mortality within an infested stand. Generally, stands on abnormally wet or dry sites sustain highest damage. In Michigan, drainage and soil moisture, along with species composition, were important determinants of SBW impact (Lynch and Witter 1985). Spruce on south-facing slopes in Maine were more severely impacted than spruce growing on north-facing slopes (Osawa et al. 1986). Vigorous trees with well-developed crowns tend to be less vulnerable than trees with low leaf area (Batzer and Hastings 1981, Blum and MacLean 1985).

Stand size and location may also be important. Mortality of dispersing SBW larvae and adults is likely to be lower in large, continuous stands of mature host trees. Thus, small scattered stands or stands of varying age classes may be less likely to suffer severe damage. Stands located downwind of current SBW outbreaks may become infested via dispersal of larvae or adults. Stands growing at elevations below 2300 ft and south of 50° latitude tend to have greatest amounts of SBW damage (Witter et al. 1984). Spruce mortality in stands at high elevation in Maine was greater than spruce mortality at low elevations (< 600 m) (Osawa et al. 1986).

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Climatic conditions likely influence SBW population dynamics. Outbreaks of SBW are often preceded by 3-4 years of early summer drought and warm, dry conditions during larval development (Wellington et al. 1950, Ives 1974, Hardy et al. 1983). Areas where climatic conditions are marginal for budworms, such as the North Shore, may show occasional abrupt and dramatic drops in SBW numbers in the midst of an outbreak (Blais 1983). Overwintering mortality seldom exceeds 15% (Morris 1963). However, cool, rainy weather and freezing temperatures may profoundly affect survival and development of feeding larvae (Luciuk 1984, 1985).

Outbreaks of SBW have occurred more frequently in this century than previously (Blais 1983). Increased frequency, severity and duration of outbreaks may be attributable to fire protection, use of pesticides against SBW and pulpwood harvesting. These activities increase conditions favorable to SBW and prolong susceptibility of spruce-fir stands (Holling 1977, Blais 1983, Blais 1985, Fleming et al. 1984). Considerable effort has been expended in the development of systems to rate stand susceptibility to SBW outbreaks (risk-rating) and vulnerability to damage if an outbreak occurs (hazard-rating). Both short-term and long-term rating systems have been used to help managers allocate resources for spray, salvage or harvest operations. A hazard-rating system was developed for Minnesota to predict potential fir morality in spruce-fir forests (Batzer and Hastings 1981). Potential mortality was estimated from pre-outbreak basal area of balsam fir and percent basal area of nonhost species. Witter et al. (1984) described a hazard-rating system used in upper Michigan. Percent mortality of balsam fir was estimated from duration of the outbreak, amount of balsam fir, site factors (e.g. drainage), and past and present management practices. In eastern Canada, a SBW vulnerability index was calculated based on volume of host species, maturity of fir and climate (Blais and Archambault 1982, MacLean 1982). Olson et al. (1982) developed procedures for estimating current and future SBW damage from aerial photos. Variables used in this system include proportion of host and nonhost species, tree condition and existing mortality of host species. Davis et al. (1980) related Shigometer readings of cambial electrical resistance to tree vigor and potential for SBW induced mortality. Numerous risk and hazard rating systems developed in eastern Canada and the U.S. are reviewed by Batzer and Hastings (1981) and MacLean (1985).

Management and Control
Severe SBW outbreaks and damage are usually associated with large stands of mature balsam fir (MacLean 1980). Silvicultural manipulation of forests to alleviate budworm impact is attractive and is generally acceptable. However the magnitude of action required on both a spatial and temporal scale is great and may necessitate management intensity not usually associated with spruce-fir forests. It should also be recognized that silviculture alone is unlikely to offer a complete solution. Budworms have periodically defoliated forests for hundreds of years (e.g. Howse 1981). Silviculture may be best applied in the context of integrated pest

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management, which utilizes biocontrol and direct suppression measures to protect forests. Silvicultural reduction of stand vulnerability may reduce the need for direct control and increase the interval between control operations (Mott 1980, Dimond et al. 1984). It should also allow more time for allocation of salvage activities and increase chances of trees recovering from defoliation (Blum and MacLean 1984).

Silvicultural strategies should be focused on reducing stand vulnerability to damage during SBW outbreaks. Blum and MacLean (1985) suggest management objectives should include removing fir early in stand development, increasing the spruce or nonhost component of the stand, and maintaining vigorous trees with high growth rates. Flexner et al. (1983) recommend the following long-term management goals: shorten rotation age of fir to 50 years, break up continuity of extensive areas of mature forest, remove fir from stand where possible, maintain a mixed species composition or convert to less susceptible species when possible, and optimize the spatial diversity of different even-aged stands on a regional basis. Lower rates of mortality and growth loss will result in decreased extent and frequency of control operations. Harvest and salvage operations can be prioritized and problems with oversupply of salvaged material may be reduced. Blum and MacLean (1984) reviewed various management systems for reducing SBW vulnerability through silviculture.

Clearcutting may be used in mature to overmature stands, stands with pest problems, or where partial harvesting could damage residual trees (Westveld 1953, Frank and Bjorkbam 1973). Clearcutting may be the most appropriate harvest method where species composition is > 50% fir, ample fir regeneration is present and the stand is densely stocked or growing poorly (Flexner et al. 1983). A major concern of clearcut harvesting is adequate regeneration. Seed dispersal from border trees may be adequate for small patch or strip clearcuts. Stripcuts are appropriate in stands with > 50% fir, moderate fir regeneration and vigorous, windfirm trees (Flexner et al. 1983). Large areas without advance regeneration may require site preparation, seeding or planting (Blum et al. 1983, Flexner et al. 1983). Clearcutting followed by stand conversion may be appropriate under specific economic or biological situations. Reforestation to reduce SBW vulnerability should favor black spruce or hardwoods over white spruce and balsam fir. In the Lake States, clearcutting followed by natural regeneration may be used to convert spruce-fir to aspen stands. At least 20 ft^2/ac of aspen basal area or seed from nearby aspen clones is required (Flexner et al. 1983). These aspen stands may develop a fir understory that will be released when the aspen is harvested. Aspen will provide protection for understory fir during an outbreak.

Clearcut harvests where advance regeneration is present function biologically as shelterwood cuts, providing seed and shade for understory trees. In shelterwood harvests, it is critical that residual SBW host trees in the overstory be removed to prevent dispersal to regenerating trees. This may

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also be a particular concern in strip or small patch clearcuts. Increased diversity may benefit natural enemies of SBW if alternate hosts are provided or habitat is enhanced (Jennings and Houseweart 1984). Strip clearcutting can also increase early-instar dispersal mortality (Jennings et al. 1983).

In shelterwood systems, the overstory is gradually removed in 2-3 harvests. This system may be conducive to seedling regeneration, limit growth of competing vegetation and offers some control over composition of regenerating species (Blum et al. 1983, Flexnor et al. 1983, Frank and Bjorkman 1983). Shelterwood harvest may be best in stands with > 50% spruce or nonhost species, inadequate regeneration, with vigorous, windfirm trees (Flexner et al. 1983). Residual overstory trees infested with SBW may require direct suppression to prevent infestation of developing regeneration.

Uneven-aged silviculture was promoted in the 1940s-1950s as a way to strongly select against balsam fir (Westveld 1946, McLintock 1947). This system may be effective in altering species composition (Blum 1978, Frank and Blum 1978). However, repeated light harvests can result in continuous cover of highly vulnerable, mature to overmature trees with abundant flowering (Baskerville 1975). Reservoir populations of SBW in overstory trees were likely to disperse down and infest younger trees. Uneven-aged selective management may be appropriate for some situations such as streamside buffers or small tracts of land (Blum and MacLean 1985). Flexner et al. (1983) suggest selection harvests in uneven-aged stands with ample spruce regeneration, a species composition of > 50% spruce or nonhost species and moderately vigorous, windfirm trees.

Thinning and partial cutting may be useful tools for altering species composition to reduce vulnerability. Objectives of partial harvests should include removal of balsam fir, removal of highly vulnerable or low vigor trees and promotion of residual tree vigor through increased space and resources. Large openings in the canopy that could decrease wind firmness should be minimized (Flexner et al. 1983, Blum and Maclean 1985). Chances of windthrow may be increased as a result of SBW defoliation and small root mortality (Witter et al. 1984). Flexnor et al. (1983) offer specific suggestion for minimizing risk of wind damage.

Salvage of dead or dying material or presalvage of vulnerable trees may reduce economic impacts of SBW defoliation and can be used to alter vulnerability. Site quality, economic constraints and many other factors will affect salvage decisions. Salvage may offset impacts of defoliation on management goals such as sustained yield and age-class regulation (Blum and MacLean 1985) Overall salvage goals, however, should include long-term reduction of SBW vulnerability.

Hazard-rating systems and population monitoring should be used to prioritize harvesting (Montgomery et al. 1982). Lake State stands with characteristics such as a large balsam fir component, poor site conditions, age above 50

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years and high volume of sound wood should be harvested first (Montgomery et al. 1982, Flexner et al. 1983). A management strategy of increased age-class and species diversity should promote dispersal mortality, decrease extent and severity of outbreaks and limit overall impacts on wood supply. Hazard-rating systems differ regionally; managers should be wary of systems not validated for their particular area (Witter et al. 1983). Pheromone sampling may help managers monitor endemic SBW populations and locate epicenters of incipient outbreaks (Witter et al. 1983). Use of pheromones for SBW survey and detection is discussed by Allen et al. (1983, 1986). Trends in SBW populations can also be monitored by sampling various life-stages. Sampling and SBW survey techniques are reviewed by Montgomery et al. (1982) and Grimble and Kucera (1984). In the Lake States, ground defoliation surveys, pheromone sampling and other life-stage surveys are usually conducted only when management objectives are threatened (Montgomery et al. 1982). Aerial surveys can provide managers with rough ideas of the extent of SBW infestations and damage on a yearly basis (Montgomery et al. 1982).

Direct control
Various situations may require foliage protection and population suppression through application of microbial or chemical insecticides. Because material registration and application technology change rapidly, direct suppression techniques will be covered only briefly. Application materials and techniques are discussed by Hansen and Dimond (1982), Dimond (1984, 1985), Helson (1985), Lewis and Dubois (1985), and Sundaram et al. (1985). In the U.S., social, environmental and political pressures generally preclude widespread application of chemical insecticides. Aerial application of Bt (Bacillus thuringiensis) is the most common suppression method today. Although other Lepidoptera may be affected, use of Bt spares natural enemies of SBW and other non-target organisms. Timing of Bt application generally depends on bud and larval development and may require more than one application (Morris et al. 1984). Efficacy is usually greater on fir than on spruce, due to greater amounts of foliage and enhanced spray protection for larvae on spruce. Stressed SBW populations near the decline of an outbreak or weakened by microsporidia infection or other factors may be most susceptible to Bt infection. Diflubenzuron, an insect growth regulator, has also been tested for use against SBW (Retnakaran 1981).

Several other biological control strategies were evaluated by a Canadian task force in 1976 (Anonymous 1976). A nuclear polyhidrosis virus (NPV) showed moderately high potential for SBW control if production and application procedures can be developed. Other tactics, including enhancement of predators and parasites, generally showed low potential for population control, especially in outbreak situations. Houseweart et al. (1984) evaluated Trichogramma minutum, an egg parasite. Trials with ground and aerial releases of parasites increased SBW egg mortality, but not sufficiently to suppress epidemic populations. Reviews of tactics and strategies to prevent SBW damage can be found in Sanders et al. (1985).

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A.1.10
Yellowheaded Spruce Sawfly - Pikonema alaskensis (Rohwer)

Life History

Yellowheaded spruce sawfly (YHSS) is a native defoliator of spruce species and is a particular problem in young, open-grown stands. In Minnesota, emergence of adult YHSS typically occurs over 3-8 days in mid-May to late June (Bartelt et al. 1982a, Morse et al. 1984). Freshly emerged females fly upwind to host trees, presumably utilizing host-derived odors to locate a suitable oviposition site (Pointing 1957, Bartelt et al. 1982a). Mating behavior was described by Bartelt et al. (1982a). Mating is not required for oviposition, but unfertilized eggs produce only males (Pointing 1957, Houseweart and Kulman 1976a). Eggs are laid on partially developed shoots, after needle elongation begins. Peak oviposition in Minnesota occurred when 80% of new shoots barely retained bud caps (Houseweart and Kulman 1976a).

Ovipositing females show marked preference for spruce growing in full sunlight (Nash 1939, Wilson 1971, Morse 1982), and defoliation is often concentrated in upper canopy levels (Houseweart and Kulman 1976b). Defoliation of released spruce was six times greater than defoliation of spruce overtopped with aspen (Morse and Kulman 1984a). Once crown closure occurs, presence of YHSS drops sharply. Preference of YHSS for sunny locations may be related to intraspecific communication and mating. The primary component of female YHSS sex pheromone is (Z)-10-nonadecenal (Bartelt and Jones 1983), which is produced by oxidation of 10 (2,2)-9,19 dienes. This oxidation occurs most readily in full sunlight (Bartelt and Jones 1983).

Eggs hatch in 4-12 days (Pointing 1957). Larvae feed preferentially on new, expanding foliage, but will also feed on old foliage. Dense populations may cause larvae to feed on cortical tissue of new growth (Wilson 1971) and new growth may be severed (Pointing 1957). Larval feeding periods vary regionally, but typically last 10-21 days in Minnesota (Valovage and Kulman 1986). Larvae complete 5-6 stadia (VanDerwerker and Kulman 1974), then drop from trees and spin cocoons just under the soil surface (Schoenfelder et al. 1978). Pupation occurs in late winter.

YHSS feeds on a wide range of spruce species in North America, but host preferences vary geographically. White spruce is the only common host in Minnesota (Pauley and Mohn 1971, Houseweart and Kulman 1976b). Host preference may relate to synchrony of bud burst and emergence of YHSS adults; bud burst of white spruce precedes that of black spruce by ca 10 days (Blais 1957). Bud burst phenology or other attributes may also affect intraspecific resistance of white spruce to YHSS. Nienstaedt and Teich (1972) observed consistent differences in YHSS defoliation among 28 seed sources, but only when infestations were light. No differences in oviposition rates were observed when YHSS adults were caged on 25 white spruce seed

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sources (Connor et al. 1982). Other traits including cortical monoterpenes, needle stiffness, serrulation and color differ among provenances, but have not been related to YHSS resistance (Nienstaedt and Teich 1972).

Survival of egg and early larval instars tends to be high in Minnesota (72-97%) (Houseweart and Kulman 1976b). No egg parasites have been recorded in Minnesota and egg mortality was attributed to desiccation, infertility or predation (Houseweart and Kulman 1976b). Parasitism of late larval instars ranged from 1.5-21% in Minnesota and was attributed primarily to Bessa harveyi (Valovage 1979, Valovage and Kulman 1983, 1986). Syndipnus rubiginosus also was fairly common in Minnesota (Rau 1976). Cocoon parasitism in Minnesota was attributed primarily to Endasys pubescens (Provancher) (Rau 1976). Cocoon predation by small mammals and insects may also be a significant mortality factor (Houseweart and Kulman 1976b, Schoenfelder et al. 1978). Effects of pathogens are largely unknown, although a "wilt" disease was reported in Maine (Duda 1953).

Contributing factors
Young, open-grown trees are most susceptible to YHSS infestation. Trees 1-6 m in height and 5-9 years old are most likely to sustain heavy defoliation and subsequent mortality (Ford 1979, 1980, Morse and Kulman 1984). Susceptibility drops sharply once trees reach 10-12 years of age (Morse and Kulman 1984b), although outbreaks in older stands have been reported (Duda 1953). Understory trees and trees in dense stands are generally not susceptible to YHSS outbreaks (Ford 1979, 1980).

Trees growing in open areas on steep, south-facing slopes tend to suffer heavy defoliation and high mortality (Morse and Kulman 1986). This may result from YHSS preference for sunny locations or low vigor of trees occupying these sites. Excessive moisture can also reduce tree resistance to YHSS. Sites with high amounts of clay and silt particles suffered heavier defoliation than sites with sandier soils during an outbreak in Minnesota (Cook 1976, Cook and Hastings 1976). Nutrients, particularly nitrogen, may affect tree resistance to YHSS. Cook (1976) found low soil nitrogen was associated with heavy defoliation, perhaps due to compensatory feeding by sawflies on low nitrogen trees (Scriber and Slansky 1981). Survival of larval YHSS was examined in a nitrogen fertilization study in Minnesota. Survival was greatest at intermediate levels (224 kg N/ha) and much lower on trees with very high and very low foliar N (Popp 1982, Popp et al. 1986). Root growth of trees in Minnesota plantations was directed towards windrows, where nutrient availability was presumably greater. Trees adjacent to windrows were larger and sustained lower defoliation than trees between windrows (Morse and Kulman 1984b).

Impact
Defoliation by YHSS can significantly impact growth. Defoliation occurs when new needles function as strong nutrient sinks and results in loss of tissue with the greatest potential photosynthetic activity. Loss of new foliage

reduces available photosynthate; shorter shoots with small, closely spaced needles are produced following heavy defoliation (Pointing 1957, Kulman 1971). Kulman (1971) showed that one year of moderate defoliation substantially reduced terminal shoot length for one year and branch shoot length for two years. Two years of defoliation reduced growth of terminal and branch shoots by 20-60%. Cook and Hastings (1976) also observed reduced terminal growth in a Minnesota plantation. Percent defoliation and tree height explained 75% of variation in terminal growth. Ford (1979) found 40% defoliation resulted in 4% loss in tree height growth and 57% loss in shoot growth. An average of 512 larvae per tree were associated with 40% defoliation. Delayed bud flush and reduced bud size are common the year after trees sustain heavy defoliation (Cook 1976, Ford 1979). Other impacts of defoliation may include loss of tree form due to terminal bud mortality and attack by secondary pests (Pointing 1957). Mortality resulting from YHSS defoliation is generally low. Morse and Kulman (1984b) reported 2-3% mortality in Minnesota plantations studied between 1974-79. However, mortality rates as high as 15% were observed in pockets usually associated with steep, south-facing slopes.

Review of annual Minnesota Forest Insect and Disease reports indicate YHSS activity was generally high in the late 1960's and early 1970's following extensive planting of spruce plantations in the Lake States in the 1960's. By 1978, most activity was concentrated in the Cloquet region. Several plantations were sprayed in 1978-79; sprays were concentrated in pockets with high populations or where mortality was likely. Although populations continued to be found in young, open-grown plantations through the 1980's, most were at subeconomic levels or confined to windbreaks or ornamental plantings. White spruce seed orchards were sprayed in 1982-84. Activity during the last few years has been low to negligible. However, populations appear to have increased markedly in 1991 (MN DNR Newsletter 1991).

Management and Control
White spruce stands should be established on appropriate sites to minimize YHSS impact. Hazard rating systems were developed and validated to assess likelihood of damage and potential problem areas in Minnesota (Cook 1976, Morse and Kulman 1986). South-facing slopes and sites with heavy, clayey soils or poor drainage should be avoided. Windrowing and other site preparation treatments should be monitored to minimize loss of organic matter and nutrients. High planting density may result in lower susceptibility to YHSS infestation and may provide greater stocking in the event of mortality. Overstocking, however, should be avoided, since stagnation or high competition may reduce ability of trees to recover from defoliation.

Once stands are established, other measures can be employed to reduce chances of YHSS damage. Thinning or release of spruce stands should be delayed until trees are ca 10-12 ft tall. A light overstory of aspen or other species may be appropriate until spruce outgrow susceptibility. Burning or

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other site disturbances that could affect small mammals and cocoon predation may need to be restricted.

Detection and survey efforts should continue until stands are past the susceptible stage. Stands should be hazard-rated to identify areas likely to be infested or damaged. Regressions developed by Houseweart et al. (1974) can be used for larval sampling and estimation of population levels. Pheromone lures for YHSS and its' parasite Syndipnus rubiginosus have been identified and can be deployed to detect or monitor YHSS populations (Eller 1982, Eller et al. 1984). However, trap catches of YHSS cannot yet be related to size of YHSS populations or defoliation.

Insecticide application in plantations or natural stands should be considered carefully. Reported mortality levels of 2-3% are likely to be acceptable, although mortality may be much greater in high hazard areas. Delayed bud flush after defoliation and mortality induced by natural enemies may reduce YHSS populations within a few years. Growth loss, however, may be a serious concern, especially if spruce are competing with other species for the site. Special situations such as Christmas tree plantations, nurseries and windbreaks may also require direct control. In addition to the inherent high value of these stands, trees will be exposed to full sunlight for many years, increasing the probability of YHSS presence.

A.1.11
Larch Sawfly - Pristiphora erichsonii (Hartig)

Life History
Larch sawfly is the most destructive defoliator of larch in North America and is the only major pest of larch in Minnesota (Kulman et al. 1974, Drooz 1985). The sawfly was first recorded in North America in 1880, but it is uncertain whether or not larch sawfly was native or introduced from Europe (Ives 1976). Early records described vast outbreaks that spread from east to west, indicating the sawfly was exotic. Later studies, including genetic analysis, suggested that it was a native species (Graham 1956, Wong 1974). Outbreaks of larch sawfly in Minnesota were first recorded in 1908-1914 (Graham 1956).

Life history and habits of larch sawfly were studied during an outbreak in Minnesota from 1952-1955 by Drooz (1960). Prepupal larvae overwinter in cocoons in the ground. Pupation occurs in spring and adults may emerge from mid-May to July in Minnesota. Reproduction is parthenogenic and males make up only 1-4% of the population. Eggs are laid in the cortex of current year, expanding shoots. Damage causes shoots to curl, a typical sign of larch sawfly activity. Each female generally lays ca 65-70 eggs. Larvae hatch in 7-10 days and feed colonially on tufts of foliage on short shoots of older twigs. Wagner et al. (1983) demonstrated that diterpene resin acids negatively affected consumption, feeding activity and growth of larch sawfly. These deterrent compounds were present in higher amounts in new needles

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than in old needles, resulting in preferential feeding by larvae on older foliage (Ohigasna et al. 1981). Larvae feed for ca 20 days, completing 5 instars, then drop to the ground and spin cocoons. Emergence and larval development may be affected by site conditions. In Minnesota, larval development was more rapid in dry sites than in bog areas. Larch sawfly is generally univoltine, although a few larvae may diapause and remain in cocoons for 2-3 winters. Sawflies of all stages may occur together in early summer due to the prolonged period of adult emergence.

Impact

Vast areas of mature tamarack were apparently killed by larch sawfly in the late nineteenth and early twentieth century. Reports from early workers in Canada were surveyed by Ives (1976). Reports included descriptions of individual trees, each containing 400 bf of lumber and volumes in one township in excess of 10 million bf. Hewitt (1912) estimated losses to larch sawfly as totaling "many billions of feet." Widespread outbreaks have been recorded since 1880 and losses have at times been severe. Beckwith (1957) estimated that 75% of tamarack were killed in an outbreak from 1910-1926. Outbreaks in Canada from 1933-1942 were estimated to kill ca 1-5% of the trees. Later outbreaks in the 1950's caused up to 20% mortality in Alberta and 18-30% mortality in Saskatchewan (Drooz 1960). Four years of moderate-severe defoliation resulted in mortality rates between 0 and 29% on sites in northern Minnesota (Beckwith and Drooz 1956). Graham (1956) reviewed early data from larch sawfly outbreaks in the Lake States.

Other impacts of sawfly defoliation include reduced annual increment, thin sparse foliage, low shoot production and branch mortality. Annual growth increment for tamarack in Minnesota was reduced by 18% on one plot and by 68-83% on four other plots during a 7-8 year outbreak (Drooz 1960).

Tamarack do not readily die from defoliation. Graham (1931) found young larch trees tolerated three consecutive years of heavy defoliation, but died after three years of complete defoliation. However, trees are rarely defoliated completely (Drooz 1985). Feeding larvae reject single needles on expanding shoots and feed preferentially on old needles in tufts due to high concentrations of deterrent chemicals in new needles (Ohigasna et al. 1981). Heavily defoliated trees usually refoliate within a few weeks (Drooz 1985).

Contributing factors

Turnock (1972) suggested populations in North America were less stable than populations in Europe due to a poorer complex of predators and parasites, less diversity in distribution and age of hosts, and catastrophic mortality like cocoon inundation which may disproportionally affect parasitized cocoons. In a Minnesota outbreak, mortality first became noticeable after six consecutive years of defoliation, particularly in areas where thin duff overlaid mineral soil and rocky outcrops (Beckwith and Drooz 1956). On bog tamarack sites, mortality was first observed after 7-8 years of defoliation. Highest stand mortality recorded by Beckwith and Drooz (1956) was 29%.

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Management and control

Biocontrol of larch sawfly is likely to be more economical than insecticide application due to prolonged adult emergence (Drooz 1975). Drooz (1960) listed and evaluated the effectiveness of various parasites and listed several vertebrate and invertebrate predators of larch sawfly. Effects of insect predators and pathogens on larch sawfly were not quantified. At least 29 species of parasites attack larch sawfly, but only 2 species, Mesoleius tenthredinus and Bessa harveyi, were common during recent outbreaks in Minnesota (Thompson 1973, Drooz 1985). M. tenthredinus, an Ichneumonid wasp, was introduced into Canada in 1913, following observations that larch sawfly had few native natural enemies. The parasite was readily established, spreading into Minnesota and initially providing up to 90% control of larch sawfly populations. However, a strain of larch sawfly, introduced with the parasite, encapsulated the parasite eggs and was resistant to M. tenthredinus parasitization (Muldrew 1953). Resistance to M. tenthredinus spread rapidly and Drooz noted in 1953 that M. tenthredinus could not be depended on for control of larch sawfly in Minnesota. Olesicampe benefactor, another Ichneumonid, was successfully introduced into Canada from Europe in 1961. Parasitism rates of 60-78% were documented a few years after the wasp was introduced (Muldrew 1967). A strain of M. tenthredinus resistant to encapsulation was located in Bavaria and subsequently introduced successfully (Turnock and Muldrew 1971). Both the bavarian strain of M. tenthredinus and O. benefactor were introduced into Minnesota in 1971 and 1972 and have contributed significantly to sawfly population regulation (Kulman et al. 1974).

Bird predation may also affect sawfly mortality, particularly at low population densities (Buckner and Turnock 1965). There were 43 species of birds utilizing sawflies to some degree in Canada and evidence of numerical responses by several species.

Climatic and phenological factors can also regulate larch sawfly populations. Impacts of weather-related variables on sawfly survival were reviewed by Drooz (1960). Extreme drought and high precipitation are both unfavorable to larch sawfly survival, although Graham (1956) noted prolonged drought preceded at least one outbreak. Excessive heat may kill feeding and cocooning larvae. Larvae emerging from eggs laid late in the season may be unable to find adequate foliage. Winter mortality can be high; in Minnesota, 77-86% of overwintered cocoons died from 1953-1956. Interestingly, trees continued to be heavily defoliated despite this level of mortality. Newly cocooned larvae may suffer high mortality if submerged under water during flooding (Graham 1956, Ives 1968). Turnock and McLeod (1966) suggested low summer temperatures could prolong larval development and reduce survival.

Ives (1976) conducted intensive life table studies in Canada. Parasitism by the Tachinid B. harveyi, O. benefactor and the bavarian strain of M. tenthredinus, and cocoon predation by rodents were important mortality

factors. Invertebrate predation was not important in regulating sawfly populations. Wet bogs or periodic flooding that inundated cocoons also caused very high mortality. Mortality from small mammal predation of cocoons, cocoon mortality from flooding and adult mortality were potential regulators of population trends but were not density-dependent. Parasitism by Q. benefactor was density dependent and could regulate larch sawfly populations. Simulations indicated outbreaks of larch sawfly in Manitoba would occur only in the absence of Q. benefactor parasitism. LeJeune (1951) similarly found soil moisture (flooding), parasites and rodent predation of cocoons to be important mortality factors.

Changes in host trees may also feedback and affect sawfly population dynamics. Foliage production may be low following 3-4 years of defoliation, resulting in starvation of larvae. Number and length of terminal shoots may also decrease, reducing the number of suitable oviposition sites. LeJeuene (1951) suggested reduced feeding and oviposition sites could cause dense populations to decline in 3-4 years while moderate populations could persist 7-8 years.

Relatively little information is available on silvicultural or management-related treatments to reduce susceptibility or vulnerability to larch sawfly. Drooz (1960) discussed use of insecticides prior to 1960 for larch sawfly control. Larch sawfly feeding preferences were found to vary among geographic strains and species of larch (Harman and Genys 1970). Selection and breeding programs could presumably be developed to enhance natural resistance.

A.1.12
White Pine Weevil - Pissodes strobi (Peck)

Life History
White pine weevil (WPW) is a native, univoltine insect. It is a particularly important pest of white pine, but also attacks jack, red and scots pine, white, black and blue spruce, white fir and other conifers. White pine weevil, along with white pine blister rust, has historically limited planting of white pine in the northeastern U.S. and Canada.

Adult weevils overwinter in duff below host trees until about April. Emerged adults are phototaxic and negatively geotropic and move immediately to tree tops. Adult weevils also orient visually to tree silhouettes (VanderSar and Borden 1977a, 1977b). Stout, vigorous leaders with thick bark are actively selected by adults and weevil populations concentrate on trees with suitable leaders (Kreibel 1954, Sullivan 1961, Dixon and Houseweart 1983). Adult feeding and oviposition sites are on the preceding years' growth, starting just below the node and progressing downward (Wallace and Sullivan 1985). Feeding males produce an aggregation pheromone that is synergistic with host volatiles and attracts both sexes (Booth and Lanier 1974, Booth et al. 1983). Five to eight adults per

terminal may be observed in high populations (Dixon and Houseweart 1983). Host acceptance by feeding weevils may depend on a complex chemical profile which includes feeding stimulants but lacks feeding deterrents (Alfaro and Borden 1985). Flight by adult weevils is common in spring, but weevils generally do not disperse far. About 65% remain within 12 m of the brood tree (Harman 1975), while up to 10% may travel 100-300 m with prevailing winds (Dirk 1964, Harman and Kulman 1967). Oviposition begins ca 1 week after emergence. One to three eggs are laid at the bottom of feeding punctures. Females may deposit up to 200 eggs per terminal in 1-year old leader internodes. Activity levels of spring adults are strongly dependent on microclimate (Sullivan 1960, 1061). Oviposition activity is especially dependent on temperature and relative humidity.

Eggs hatch in ca 2 weeks. Larvae form feeding rings around the circumference of the leader and feed downward, consuming inner bark. Larvae pass through 4-5 instars and complete development in 5-6 weeks (Harmon 1970). The number of larvae in the feeding ring decreases as larvae grow (Dixon and Houseweart 1982). Larvae feeding singly may be killed by cortical resin when resin ducts are cut (Overhulser and Gara 1981). Intraspecific competition is intense within brood trees. Young larvae and eggs may be overtaken as older larvae feed downward (Dixon and Houseweart 1982). Competitive interactions ensure maximum production of mature larvae from a limited food resource (Wallace and Sullivan 1985).

Pupation occurs in chip cocoons formed in the pith or wood of dead leaders. Pupal chambers are usually located 1-2 years below current growth. Adults emerge in ca 2 weeks, although callow adults may remain in pupal chambers an additional 2 weeks. Observation indicates only 3% of eggs complete development and emerge as adults in the fall (Sullivan 1961). Adult emergence generally occurs during August-September. Emerged adults feed, usually on or near brood trees (Godwin et al. 1957). Fall feeding may occur on upper lateral shoots, terminals, and other areas of the crown. Adults eventually move down trees and hibernate near host tree boles (Dixon et al. 1979). Adults do not achieve sexual maturity until the following spring. During the fall feeding period, no aggregation pheromone is produced and adults are solitary. Under certain weather and site conditions, adults may live 2-4 years (Dixon et al. 1979).

Factors causing mortality to WPW populations were examined in a study in Maine (Dixon and Houseweart 1982). Major determinants of population trends were survival of larvae, pupae and overwintering adults. Factors causing mortality in these stages included intraspecific competition among larvae, pitch drowning of larvae and pupae, natural enemies and environmental variables acting on overwintering adults. One Dipteran and two Hymenopteran parasites were recovered. The Hymenopterous parasites and one insect predator appeared to respond numerically to fluctuations in WPW populations. The authors noted the low mortality of eggs and the lack of data on adult dispersal and mortality in the fall. They also observed that

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WPW populations were relatively slow to change, which corroborated earlier observations by Sullivan (1961). A microsporidian was isolated from WPW populations in Ontario (Wilson 1984). Infection rates were 16% for larvae and 9% for adults. The role of pathogens on WPW population fluctuations is poorly understood.

Impact
Weevil damage results in growth and productivity loss, and distortion of tree form. Feeding by WPW larvae kills a minimum of two years terminal growth in white pine, causing the "shepards crook" typically associated with weevil attack. In some cases, up to four years of growth may be lost in an single year (Marty and Mott 1964). A lateral branch eventually assumes dominance, but crook, forks and acute (often bark-encased) branch angles are common (Marty and Mott 1964). Marty and Mott (1964) observed 1-2 weevil injuries per 16 ft of merchantable bole. Repeatedly attacked trees may be killed by suppression and the inability to compete with other vegetation (Alfaro and Borden 1985).

Impact of WPW in white pine plantations depends on the percentage of trees affected. In open-grown white pine stands in Ontario, 64% of leaders were attacked and 45% of these died (Sullivan 1961). Gross (1985) estimated 20% of trees in an Ontario plantation were damaged and estimated annual loss in volume of 10,400 m^3. Brace (1972) examined second-growth white pine stands in Ontario. Reduced volume and lumber degradation were related to the number of weevil injuries and tree size. Decreased lumber value resulted from damage such as cross grain, reaction wood, wane due to sawing through crooks, and bark-encased angle knots. Angle knots occurred where lateral branches below weevil-damaged terminals failed to become leaders. Value reduction of 1-3 grades was more serious economically than volume loss in sawlogs and decreased with tree size. Volume losses of 3-21% were most important to fiber-product (pulp) yield. Waters et al. (1962) found a mean 13% volume loss in pole-sized stands in New Hampshire, which amounted to a loss of 35 million ft^3 when extrapolated across the state. Volume loss in sawtimber stands due to reduced height, defects and increased taper amounted to an average of 40% or 2.16 billion bf if extrapolated across the state. Overall, 87% of white pine trees sampled were damaged by WPW. Weevil damage in northeastern stands reduced volume by 22-63% and all 20 plots surveyed sustained damage (Marty and Mott 1964).

Contributing Factors
It was recognized early on that WPW damage was much greater in open stands than in dense stands, and that trees mixed with or shaded by hardwoods were rarely attacked (Graham 1918). Weevil damage was evident in virgin pine forests of colonial America, but became abundant from the late 1800' -1920's (Wallace and Sullivan 1985). Natural establishment of poorly stocked white pine on abandoned farmland combined with establishment of several plantations resulted in considerable damage by WPW.

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It is now understood that shading plays an important role in susceptibility of trees to WPW. Work by Sullivan (1961) showed that microclimate and characteristics of tree terminals determine whether a tree will be attacked by adult weevils. Bark temperature is critical in regulating weevil activity, especially oviposition. Trees in shaded stands may have temperatures 3-11 °C cooler than trees in open stands, and are unsuitable for weevil oviposition. Larval development in shaded stands is prolonged and few weevils successfully overwinter. Adult weevils released in heavily shaded stands dispersed to sunny areas or died. Weevils also exhibit a distinct preference for thick, vigorous leaders which are typically found on open-grown trees. Average diameter of terminals of open-grown trees was 9.3 mm compared to 3.9 mm in shaded stands. Weevils generally will not attack terminals less than 4.0 mm in diameter. Stands shaded by a hardwood canopy may be vulnerable before leaf expansion in spring. However, most weevil adults are not physiologically ready for oviposition that early and physical attributes of leaders are not suitable. Differences in WPW damage between dense stands and open stands relate to greater shading and smaller terminal diameter of trees in dense stands (Stiell 1979).

Tree size is also important. Although taller trees may be attacked, most concern is with trees up to 5 m high. Trees achieving 5 m in height without WPW damage will produce at least one sawlog without defects.

Management and Control
Silvicultural management of WPW is directed at providing shade to susceptible trees to inhibit WPW attack, particularly when plantations are established on old fields or in the vicinity of WPW populations (Stiell 1985). Most silviculture regimes attempt to protect white pine by underplanting, shelterwood, and partial hardwood cover until regeneration reaches a height of 5 m (one log-length) (Stiell and Berry 1985). Reduction of insolation by 60-80% results in negligible damage (Sullivan 1961). When insolation is reduced by 25-50% damage occurs, but is still only one-tenth of that of open grown stands.

The need to provide shade must be balanced, however, with the need to minimize competition with other vegetation, which could lead to suppression or mortality. Stiell (1979) evaluated an Ontario plantation established in 1939 at very high stocking (22,900 trees/ha). By 1958, most trees had reached 5 m in height, stocking levels were 10,000 trees/ha and 60% of trees had escaped WPW damage. Diameter growth was very slow, however, and competition resulted in high mortality to unweeviled trees in lower crown classes. A precommercial thin at 19 years released undamaged trees, resulting in higher growth and lower mortality rates than the unthinned control. The author concluded that dense stands should be thinned after most reach a height of 5 m, but before the number of unweeviled trees drops below 370 trees/ha. Brace (1972) recommended thinning plantations to remove WPW damaged trees and concentrate growth on residual trees.

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In Ontario, shelterwood management is preferred on ca 50% of districts and was described by Stiell (1985). The existing stand provides both shade and seed. The overstory is removed in 2 or more cuts late in the rotation. An initial preparatory cut promotes crown expansion and seed production. Then a seed cut is implemented to provide space for seedlings. Finally, residual trees can be removed after regeneration is established. Benefits of shelterwood management include production of shade to inhibit weevil attack, inhibition of competing vegetation, continuous seed supply, accelerated diameter growth of final crop trees due to partial cuts and preservation of amenity values. Disadvantages include higher logging costs, possible logging damage, and the need to sell material from each partial cut.

Clearcutting is also common in Ontario and is used in overmature stands and where seed supply is insufficient or unreliable (Stiell 1985). Logging costs are generally low. However, site preparation is often required, seedlings are subject to drying and WPW damage, amenity values may drop and artificial regeneration is expensive (Stiell 1985).

White pine may also be managed through seed tree cutting. One cut is made, leaving up to 35 trees/ha for seed production. Costs and benefits are similar to clearcutting. Seed supply is improved unless the seed source is lost to fire or windthrow. On some sites (e.g. dry soils unlikely to be damaged) seed trees may be removed after regeneration is established. If the stand includes a hardwood overstory, some protection from WPW may be accrued if hardwoods are left.

Stiell and Berry (1985) examined a harvest method to provide side shade utilizing north-south strip cuts in an Ontario plantation. Ratio of strip width to stand height was 0.66:1.00. Average height of open-grown trees was 3.3-4.0 m when first attacked by WPW. Tallest trees were attacked first and some trees were attacked up to 9 times in 18 years. Incidence of WPW attack decreased at reduced insolation rates, and was lowest at 25% insolation. Trees grown in strips required release to prevent mortality from suppression. Strips adjacent to hardwood stands were not adequately protected from WPW damage. This method provided better control of light conditions than partial or shelterwood cuts and avoided problems associated with later overstory removal (Stiell 1985).

Resistance to weevil attack may vary among genotypes and could lead to breeding and selection programs to reduce white pine susceptibility. Zsuffa (1985) reported that attempts to select traits for weevil resistance such as narrow crown and slender leaders were complicated by the influence of environmental variables. Wilkinson (1983) found leader and growth characteristics explained relatively little variation in white pine susceptibility. Kiss and Yanchuk (1991) reported incidence of weevil damage was negatively related to height and diameter growth of interior spruce families. They suggested selection of fast-growing spruce families could improve genetic resistance to weevil attack. Resistance may be related to genetically-

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based tree defence mechanisms rather than differential attack by adults weevils. Presence of strobic acid in oleoresin may determine whether larvae survive or drown in pitch (Santamour and Zinkel 1976). Results of efforts to screen cortical resin crystallization in white pine for resistance to WPW are equivocable so far (Wallace and Sullivan 1985, Zsuffa 1985). Other workers suggest resistance may be related to cortical terpenes and possible repellence of adults (Bridger at al. 1979, Wilkinson 1980). Alfaro and Borden (1985) examined feeding stimulants and deterrents and suggested chemical profiles, along with morphological traits, may be useful for selecting resistance to WPW.

Chemical control of WPW may be appropriate until white pine reaches 20-30 years of age (DeGroot 1985). This stage is critical for production of straight sawlogs and is concurrent with microenvironmental conditions most conducive to WPW presence. Chemical suppression is likely to be expensive and repeated applications may be required (Stiell 1985). Only adults are susceptible to chemical treatment. Timing of application and complete coverage of terminal buds and leaders are critical but difficult to attain (DeGroot 1985). Aerial spray of trees over 3.65 m tall may be required, but coverage is often imperfect (Stiell 1985).

Cultural control may be appropriate in some situations. Infested terminals and top-whorl leaders can be clipped and destroyed when small areas or ornamental trees are affected. One top-whorl leader should be retained to assume dominance (Stiell 1985). Dixon et al. (1979) suggested raking or burning duff might suppress overwintering WPW populations.

A.1.13
Jack Pine Budworm - Choristoneura pinus pinus Freeman

Life Cycle
Jack pine budworm (JPBW) is a native, univoltine insect and the primary defoliator of jack pine. Eggs are laid on one-year old needles in mid-summer, and hatch in 10-14 days. First instar larvae do not feed, but disperse via silking in search for suitable overwintering sites. Larvae construct silken hibernaculae in bark crevices, molt to the second instar and enter diapause-mediated dormancy. Second instar larvae resume development in spring; larvae emerge from hibernaculae in late May or early June, then disperse to find feeding sites. Larvae feed on expanding, current-year needles. However, when staminate flowers are present, larvae will feed preferentially inside cones, until pollen is shed and cones dry out. During outbreaks, a shortage of new foliage may cause larvae to also consume older foliage (backfeeding). Larvae continue to feed on expanding foliage, typically clipping off and webbing needles together with silk. Later instars may silk several new shoots together, and clipped foliage, silk and frass become increasingly conspicuous. Desiccation of clipped and webbed foliage results in the reddish appearance of trees, characteristic of JPBW damage. Larvae pass through 7 instars (Nealis 1987). Adults emerge from pupae in

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6-10 days, mate and complete oviposition in 3-5 days. Although jack pine is the principal host of JPBW, red pine, Scots pine, lodgepole pine and white pine may also sustain damage (Prentice and Nairn 1958, Kulman and Hodson 1961b, Howse 1986, Anonymous 1989).

Outbreaks of JPBW tend to occur at roughly 10 year intervals, although some areas sustain chronically high populations (Volney 1988, 1989). High populations generally persist 2-4 years, then decline. Heavy defoliation rarely occurs on the same trees for more than 2 consecutive years (Alan Jones, MN DNR, pers. comm.). Analysis of time-series data from prairie provinces of Canada suggested JPBW outbreak areas were correlated with areas sustaining large-scale fire activity in the preceding 4-7 years (Volney 1988). This correlation indicated dry years resulting in increased fire activity may provide conditions suitable for JPBW population build-up in subsequent years. Outbreaks tend to occur synchronously over large geographic areas. In the mid-1980's, JPBW outbreaks occurred in Ontario, Manitoba, Saskatchewan, Michigan, Wisconsin and Minnesota (Volney 1989). Dynamics of localized populations may, however, be highly variable. Life-table studies were conducted by Foltz et al. (1972) in Michigan, and by Batzer and Jennings (1980) in Minnesota. Spring and autumn dispersal of larvae, overwintering mortality, and parasitism (primarily Apanteles spp. and Glypta fumiferanae) were important mortality factors. Much mortality of larvae and pupae was attributed to "unknown sources." Pathogen effects were not directly assessed in the life-table studies. Indirect evidence and observation indicate, however, that pathogens such as microsporidia and bacteria may contribute to mortality of larvae and pupae (Volney 1989, Vince Nealis, Canadian Forest Service, pers. comm., D. McCullough, unpub. data).

Other authors have examined parasitism of JPBW in more detail. Surveys indicated Apantales spp., Itoplectis conquistor and Glypta fumiferanae were important JPBW parasites (Kulman and Hodson 1961a). Elliott et al. (1986) described the JPBW parasite complex in Michigan. An egg parasite, Trichogramma minutia was identified in Wisconsin (Dixon and Benjamin 1963), but did not exhibit functional or numerical response to JPBW density (Foltz et al. 1972). Similarly, Tachinid parasitism and bird predation contributed to JPBW mortality in Michigan, but showed limited numerical response to JPBW density (Foltz et al 1972). Parasitism of larvae in Ontario by Apantales fumiferana and Glypta fumiferana slowed feeding and development, and larvae usually succumbed by the fifth or sixth instar (Nealis 1987).

Weather appears to play a critical role in JPBW populations, but causal effects of climatic variables on JPBW dynamics have not been determined. Clancy et al. (1980) developed regressions relating numerous climatic variables to JPBW populations in northwest Wisconsin. They noted, however, that evidence was correlative only; mechanisms relating weather to JPBW dynamics were not determined. Climatic conditions that favor

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staminate flower production may also favor JPBW survival. Staminate flowers may reduce mortality of early larvae by decreasing dispersal loss or by providing a refuge for larvae emerging prior to foliage expansion (Hansen 1988, Jan Volney, Canadian Forest Service, pers. comm.). Other factors thought to contribute to JPBW mortality include high humidity and rainfall, cool temperatures, fluctuating and severe winter temperatures, and high winds during spring dispersal of larvae (Rose 1973, Robert Heyd, MI DNR, pers. comm.). Mild winters and warm, dry conditions in spring may favor JPBW survival.

Impact
Severe defoliation may result in tree mortality, especially to stressed or low-vigor trees. Mortality due to JPBW defoliation is generally low in well-stocked stands and is usually concentrated in suppressed, understory trees (Benjamin et al. 1961). Severe and repeated defoliation, however, may kill larger trees and seedlings, particularly in poorly stocked stands. Kulman et al. (1963) found a Minnesota JPBW outbreak in the 1950's resulted in 29-44% mortality of completely defoliated trees. They observed 2-13% mortality in young, pole-sized trees, 10-12% mortality of saplings (4 inches dbh), 58% mortality of young saplings (2 inches dbh) and 90% mortality of heavily defoliated understory reproduction. A 1954-57 outbreak in Wisconsin resulted in mortality of 1-8% of merchantable trees (Benjamin et al. 1961). Graham (1935) reported 2% mortality of dominant trees during an outbreak in Michigan. During a 1980-82 JPBW outbreak in lower Michigan, 233,000 ha were severely defoliated. Mortality rates averaged 35% on 141,000 ha and 10% on 108,000 ha (Robert Heyd, unpublished MI DNR Pest Report 1988). Probability of tree mortality increases if outbreaks coincide with or are preceded by drought (Robert Heyd, MI DNR, pers. comm.). Feeding by pine sawflies on old foliage has exacerbated effects of even light defoliation by JPBW (Shane Weber, WI DNR, pers. comm.).

Significant growth loss and loss of tree form due to upper bole and branch mortality (top-kill) are typical consequences of JPBW defoliation. Kulman et al. (1963) found severe budworm defoliation virtually eliminated wood production in the year of defoliation. Radial growth was reduced by 86-100% two years after heavy defoliation and 0-83% two years after light-moderate defoliation. Rose and Brodie (1973) reported that realized yields in northwest Wisconsin were only 33% of volume predicted from standard yield tables. Volume losses were attributed to JPBW defoliation. Cerezcke (1986) estimated volume losses from JPBW defoliation based on pre-outbreak growth. Decline in annual increment occurred in the third year of outbreak with maximum reductions of 54% and 91% on two sites. Top-kill occurs frequently due to concentration of JPBW defoliation in the upper crown (Graham 1935). Seven to 50% of terminals were killed after a JPBW outbreak in Minnesota (Kulman et al. 1963). In Ontario, 2-4 years of moderate-severe defoliation resulted in top-kill of up to 40% (Kondo and Taylor 1986). Defoliation also increases susceptibility of jack pine to attack from pathogens and secondary insects (Kulman 1971).

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Feeding by JPBW larvae can damage male and female cones. Scoring and occasional boring of first and second year female cones was observed on trees with light-medium defoliation (Kulman et al. 1963). Male cones may be damaged directly and pollen production may be reduced for 3 years on heavily defoliated trees. Reduced cone production combined with up to 90% mortality of understory reproduction (Kulman et al. 1963) suggests natural regeneration of jack pine can be dramatically impacted by JPBW outbreaks.

Jones and Campbell (1986) and conditions described in Annual Forest Insect and Disease Reports provided information on the recent status of JPBW in Minnesota. Infestation of JPBW in Minnesota was not regularly surveyed until 1965. High JPBW populations were documented from 1965-69, producing scattered top-kill and mortality in west central and northwest Minnesota. Aerial sprays were conducted in 1966-69 to protect two state nurseries and one campground. Heavy defoliation occurred again in 1976-80. This outbreak peaked in 1978, with ca 68,000 ac of moderate-severe defoliation. Populations generally remained low from 1981-85, with 2000 ac of defoliation, concentrated in northeast Minnesota. Epidemic populations built-up again in 1984, resulting in an outbreak from 1984-86, with 210,000 ac of JPBW activity in 1984. Populations declined in 1986-87. Areas with moderate-severe defoliation corresponded to areas previously defoliated during outbreaks in the 1960's and late 1970s. Drought and occurrence of tarspot needlecast disease were associated with increased damage in some areas during the latest outbreak.

Contributing factors
Information on traits associated with stand vulnerability to JPBW have been reviewed in the Jack pine Budworm Information Exchange (1986) and in a JPBW impact study developed for Ontario (Anonymous 1989). Poorly stocked stands, over-mature stands or stands with low-vigor trees are most susceptible to build-up of JPBW populations (high risk stands) and most vulnerable to damage when outbreaks occur (high hazard stands). Understocked stands with "wolf" or orchard-type trees tend to produce abundant crops of staminate flowers, which may be associated with high survival of early instars. Overstocked stands, with high competition for water, nutrients and light, may also produce abundant staminate cone crops. Suppressed and slow-growing trees with fewer carbohydrate reserves are also less likely to survive heavy defoliation than vigorously growing trees. Although underlying mechanisms are not well understood, mature to overmature trees are most susceptible and vulnerable to JPBW. Seedlings and young (< 20 years old), vigorously growing jack pine are relatively resistant to JPBW. Infestations of JPBW and severe defoliation rarely occur in stands less than 25 years of age. Multistoried stands may favor survival of early instars due to reduced mortality of dispersing larvae (Batzer and Jennings 1980). Understory trees in multistored stands are also likely to sustain heavy defoliation and high mortality (Kulman et al. 1963).

In Minnesota and other Lake States, jack pine frequently occurs on sandy, excessively drained soils with poor moisture and nutrient-retaining capacity (Cayford 1970). Trees growing on poor sites (e.g. SI < 50-55) tend to be less resistant to JPBW outbreaks and are less able to recover from heavy defoliation. In Michigan, sites where the water table is more than 6 feet deep are more likely to suffer heavy defoliation during JPBW outbreaks than areas with higher water tables (Heyd, MI DNR). Recent observations in Canada suggest presence of Armillarea may increase damage from JPBW populations (W.J.A. Volney, Canadian Forest Service, pers. comm.).

Management and Control
Much of the management of JPBW in the Lake States involves optimal allocation of annual allowable cut and maintenance of tree vigor. Recommendations for management of JPBW are discussed and compared in the Jack Pine Budworm Information Exchange (1986). Optimal stocking levels for jack pine range from 17-35 m^2/ha for stands 25 years old and older. Maintaining optimal stocking should maximize larval mortality during dispersal, minimize staminate flower production and reduce defoliation intensity (Batzer and Jennings 1980). Overstocked stands should be thinned from below (pulpwood thinning) where economically feasible. Stands with < 14 m^2/ha should be harvested. Wolf trees should be selectively removed. Jack pine should not be stored on the stump due to high risk and hazard associated with overmature trees. Optimal rotation age is dependent on site quality, but will usually range from 25-50 years in the Lake States. Jack pine can be held longer than 50 years only on the best sites (SI > 70) (Jones & Campbell 1986). Stands with SI < 55 should be harvested by age 40, since stand break-up from JPBW damage, bark beetles, pathogens and breakage is likely (Robert Heyd, MI DNR, pers. comm.). Large, expansive stands of jack pine (e.g. > 260 ha) should be avoided. Optimal stand size should be limited to 25-65 ha or less. Buffer strips, five chains wide, can be planted with other species and used to reduce chances of large-scale fire or JPBW outbreak. Even-aged stands are less likely than uneven-aged stands to sustain damage or allow JPBW population build-up. However, a mosaic of diverse age-classes should be promoted in large jack pine areas.

Several hazard and risk rating strategies have been developed and can be used to prioritize stand harvesting. Components of hazard rating systems used in Minnesota were reviewed by Jones and Campbell (1986). Several survey systems have been developed to estimate JPBW population levels and defoliation (Foltz et al. 1968, 1971, Jones and Campbell 1986, Meating 1986). Information from surveys can be used to locate and predict JPBW damage and to prioritize stands for further sampling, harvest or salvage efforts. Isolation of the female sex pheromone of JPBW stimulated interest in utilization of pheromone traps to detect or monitor populations (Jones and Campbell 1986, Anonymous 1989). Trials indicated more development is needed before pheromone trapping is operational. Trap catches in Minnesota prior to 1986 were generally poorly correlated with estimates from populations surveys.

Direct control of JPBW should be carefully considered due to environmental and economic considerations. Cost/benefit analysis of JPBW control in Michigan indicated chemical application could rarely be economically justified (Nyrop et al. 1983). Brodie and Rose (1975) used simulation models to compare profitability of varying levels of management intensity and insect damage. Spray operations in Minnesota have been generally limited to high value trees, such as campground or recreation areas, nurseries or ornamentals. Areas prone to chronic JPBW infestation may be converted to red pine, white pine, aspen or scrub oak in some cases (Weber 1986).

Observations by Minnesota DNR pest specialists indicated damage sustained during the outbreak in 1984-86 was generally much less severe than that sustained during the outbreak in the late 1970's. In the 1970's, defoliation resulted in several instances of total stand mortality and salvage was required in two counties. Losses were greatest on drought soils, rocky outcrops and ridges. Damage from the 1980's outbreak consisted primarily of top-kill, with little mortality. Reduced damage was attributed to management efforts to regulate age-classes, preferential harvest of older, overmature stands, and reduction of open-grown stands.

A.1.14
Ips Pine Engraver Beetles - Ips pini Say

Ips pini, the pine engraver, is common and widely distributed in North America. Numerous hosts can be infested, including many species of pine and spruce. The pine engraver has been known by various scientific names due to its wide host and geographic range (Coulson and Witter 1984).

Ips beetles are secondary borers, usually breeding successfully only in severely stressed trees, felled trees and slash. Vigorously-growing trees defend themselves from bark beetle attack by producing a copious flow of resin to "pitch out" beetles as they bore into stems. When tree vigor is reduced, oleoresin flow and exudation pressure drops, resulting in successful penetration and gallery construction by beetles. Drought stress, flooding, injury to roots or stems, defoliation by other insects, pollution and pathogens may predispose trees to bark beetle attack and allow Ips populations to build. Subsequent mass attacks by high populations of beetles can result in colonization and death of healthy trees. Even when infestations are restricted to tree crowns, the resulting loss of vigor and possible colonization by other pests may lead to mortality. In the Lake States, red and jack pine, and occasionally white pine, are attacked by Ips.

Life History
Schenk and Benjamin (1969) described the biology of Ips beetles in central Wisconsin. Much of the following material in this section was extracted from their report, unless otherwise noted.

Mature adults overwinter in litter and duff near host trees. Spring emergence of Ips beetles in Wisconsin occurred in late May when temperatures remained at ca 16.7 °C, with daily mean maximum of 22.8 °C and minimum of 10.0 °C for a week. Males bore entrance tunnels into tree boles and constructed nuptial galleries. Females enter tunnels bored by males, mate and construct galleries for oviposition. Each Ips male may service 3-5 females. Ips beetles preferentially attacked tops of logs in Wisconsin and may have preferred insulated sides of logs to shaded sides. However, preferences were not evident when gallery density was high.

Completed egg galleries are often Y or H-shaped, run vertically and are usually 7-10 cm long. Single females in Wisconsin excavated 1 cm of gallery per day; longest observed galleries were 15-19 cm long. Number of eggs per gallery in Wisconsin averaged 16-22 and egg number was inversely related to population density. About 5 days were required for construction of entrance tunnels, mating and oviposition. Adults may re-emerge following oviposition and attack new hosts, but this has not been determined for many host species.

Eggs hatch in 5-6 days. Larvae feed in the phloem-cambial area in galleries at right angles to egg galleries and pass through 3 instars. In Wisconsin, pupation occurred in 10-15 days and lasted 6-7 days. Mature F_1 adults appeared 31-37 days after initial attack, but fed in the cambium 5-11 days before emerging. Three generations were completed annually, with peak occurrence of adults in mid-July (F_1), early September (F_2) and mid-October (overwintering F_3). An average of 36 adults emerged from 1 ft^2 of bark surface on heavily infested trees. In Minnesota, 2-3 generations are usually produced, although 4 generations occurred during the severe drought in 1988.

Susceptible hosts are mass attacked by males and females. Attack, colonization and beetle density is regulated by beetle-produced pheromones and host attractants. Lanier et al. (1972) evaluated reciprocal attractiveness among logs infested with males from New York, Idaho and California populations. Although adults from the three populations interbred freely, there were distinct regional variations in attractant pheromones and receptors. Further work indicated that geographic variation in the enantiomeric composition of ipsdienol caused regional preferences (Lanier et al. 1980). Adults may communicate acoustically within hosts (Barr 1969, Coulson and Witter 1984).

Adults inoculate hosts with fungi transported in mycangia. The fungi, usually blue-staining Ceratocystis spp., are important in killing host trees and may provide some nutrition to developing beetles (Coulson and Witter 1984). Response of red and jack pine to fungi vectored by Ips pini was examined in Wisconsin (Raffa and Smalley 1988a, 1988b). Both red and jack pine survived at least three growing seasons following inoculation. Lesion formation in trees differed between two Ceratocytis species and was affected

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by season of inoculation. Short-term response of trees to inoculation was greater for jack pine, but continued expansion of lesions in red pine resulted in a greater long-term response.

Inter- and intraspecific competition can contribute greatly to mortality of Ips broods. In Wisconsin, Cerambycid larvae destroyed up to 50% of eggs and first instar larvae. Adult feeding also caused mortality to eggs and first instar larvae of late broods. Intraspecific competition by Ips was the most important mortality factor in natural infestations.

Natural enemies also affected Ips mortality in Wisconsin. Clerid, Histerid and Staphylinid beetles were the most common predators. Maximum predator populations coincided with the appearance of callow F_1 adults, ca 26 days after initial beetle attack. Lanier et al. (1972) found a predaceous Clerid beetle and a Hymenopteran parasite could distinguish subtle differences in pheromones and exhibited a preference for local populations. Raffa and Klepzieg (1989) identified chiral preferences of predaceous Clerid beetles in Wisconsin, who use ipsdienol to locate their prey.

Impact
Discolored foliage is usually the first indication of Ips infestation. Needle color fades from green to yellow, eventually turning red from late June through September (Eiber et al. 1989). "Faders" and dead trees often occur in clusters or pockets since emerging beetles usually attack hosts adjacent to brood material. Trees attacked late in the summer may remain green through winter. These trees often contain partially developed larvae and may be debarked by woodpeckers searching for the larvae (Banash et al. 1977). Attack of trees often begins in tree tops and progresses downward. Boring dust and small, round holes on main stems and large branches indicate bark beetle presence. Galleries are less than 1/16 in wide and can be observed by peeling off bark and examining the inner bark and wood surface. Ips galleries have a central nuptial gallery, then 3-5 egg galleries radiating from it in a Y or H shape.

Relatively little information has been published on damage or impact of Ips pini in the Lake States. Annual insect and disease reports from 1978-1989 of the Minnesota Department of Natural Resources were surveyed to evaluate Ips-related damage in Minnesota. In most years, tree mortality was associated with plantations or stands where slash or windthrown trees contributed to population build-up. Populations of Ips began to build in 1987 and became very serious in 1988 during the drought. In much of Minnesota, 80-90% of red pine plantations had active Ips infestations in 1988. Mean mortality in 1988 ranged from 5% in southeast Minnesota up to 10-12% in the central part of the state. Combined losses in a 5 county area (Sterns, Benton, Sherburne Kanabec and Anoka) amounted to over a million trees. White pine on bluff sites in Fillmore and Houston counties were also killed. Temperatures were not as high in 1989 and drought conditions were somewhat ameliorated. However, 1-2% mortality continued over the winter

in red pine stands. Most mortality was again associated with thinning operations or near homebuilding sites. The fact that the 1988 drought was a relatively rare event (150 year drought) combined with recently issued pine management guidelines suggests future impacts may be less severe than those recently experienced.

Contributing Factors
Little information on factors contributing to Ips beetle attack has been published in the Lake States region. The material below, unless otherwise noted, was acquired from annual insect and disease reports published by the Minnesota Department of Natural Resources.

Drought stress is a common and critical factor affecting host susceptibility to attack to Ips. In Minnesota, drought stress was repeatedly implicated as the predisposing factor where Ips damage occurred. In 1988, during extremely severe drought, 3-4 generations of Ips beetles occurred in Minnesota and caused high mortality. Although drought conditions were alleviated somewhat in 1989, trees continued to be stressed and Ips-related mortality continued through the winter. Banash et al. (1977) reported that low soil moisture due to low water-holding capacity of coarse, sandy soil or extended drought was the most common source of pine tree stress. Schenk and Benjamin (1964) found moisture content of increment cores extracted from Ips infested trees in Wisconsin was lower than that of uninfested trees. Moisture content was related to live crown ratio and oleoresin production. Susceptibility to Ips beetles was estimated by the amount of live crown and radial crown fullness. Trees with full, symmetrical crowns making up 33-50% of the height were considered resistant, while large wolf trees, intermediate and poor codominant trees were most susceptible.

Damage resulting from other environmental factors may also stress trees or lead to Ips outbreaks. Trees damaged by wind or lightening often provide good brood habitat. In one case, a tree struck by lightening was later infested with Ips. Within several weeks, 150 red pines (60 ft tall) surrounding the brood tree were infested and dying. High mortality was observed in another red pine plantation where surrounding stands had been harvested. Some residual trees were windthrown; Ips beetles colonized these trees, then attacked others in the stand. Flooding may also stress or kill trees. High water tables in areas of Minnesota in 1987 killed several trees. Ips broods developed in these trees, then attacked adjacent stands during a drought period in the summer. Attack by other insects and pathogens, notably jack pine budworm and Armillaria root rot, may also stress trees and predispose them to Ips attack.

Silvicultural activities such as thinning, pruning, and harvesting may provide brood material for Ips beetles, leading to subsequent problems. Unlike other bark beetles, such as Dendroctonus spp., Ips beetles successfully colonize slash down to ca 2 inches in diameter. Slash left in red pine plantations after thinning and pruning operations has resulted in Ips-related mortality in

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Minnesota red pine plantations annually. Ips populations may also build up when trees are felled but not removed from stands or plantations. In a few instances, weak markets caused jack and red pine to be cut and left on landings or decks in timber sale areas. Ips beetles subsequently attacked residual trees or trees in adjacent stands. Thinning or clearcut harvests also open stands up to wind damage, increasing available brood trees. However, stagnate plantations left unthinned due to weak pulpwood markets were also damaged by Ips. Ips problems may be especially severe when freshly cut material is present in the spring and summer during adult beetle emergence. Fresh slash may allow overwintering adults to be highly successful, resulting in high populations capable of attacking healthy trees in subsequent generations. Other human-caused stress can also predispose trees to beetle attack. Problems have arisen previously in urban/wildland interface areas where soil compaction and wounds to stem and roots are common. Ips infested firewood stacked near conifers has also caused problems in past years.

Management and Control
Guidelines for bark beetle management in pine stands were published by the Minnesota Department of Natural Resources (Anonymous 1989). These guidelines are designed to prevent infestation and damage by Ips beetles and are briefly summarized below. The state was divided into a northern and southern zone. In the northern region, slash should be generated during the preferred period from August 1 - March 1. In the southern zone, slash can be generated from September 1 - February 1. Merchantable material should be removed from all stands by May 1. All timber sales must include a statement regarding requirements for removal and destruction of slash during bark beetle risk periods. If cutting occurs beyond preferred periods in the respective zones, all residual material above 4 inches in diameter must be removed or treated to prevent beetle attacks by May 1. After May 1, treatment must occur within 3 weeks of cutting. During extended drought periods, material larger than 2 inches in diameter must be removed or treated to prevent attack. Full tree skidding should be used to harvest pine stands. Slash should be piled to allow burning if necessary. If short wood skidding is used, a slash free alley of 15-20 feet should be maintained around the sale to allow burning of residual material. To enhance drying, slash should not be lopped or piled if burning is not planned.

The following restrictions are applicable to all thinning operations and are again designed to prevent Ips damage. Thinning should occur during the preferred periods. However, during drought periods, no thinning should take place. All cut material greater than 4 inches in diameter should be removed by May 1. Thinning and pruning should not occur during the same growing season. No more than 50% of the basal area should be removed in a thinning operation. All operations other than thinning or cutting should be confined to the preferred periods. Where infestations already exist, salvage operations may allow recovery of some material.

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Wisconsin guidelines are similar to those of Minnesota and were described by Banash et al. (1977). Cutting operations in Wisconsin should be avoided between April 1 and September 1. If any operations occur between these dates, material larger than 2 inches in diameter must be removed within 3 weeks. Needles should be left attached to branches to speed drying of unmerchantable stem wood. Plantations should be thinned back to 80-90 ft^2/ac when 25-30 years old or when basal area exceeds 180 ft^2/ac. Stagnating trees or stands on wet or low nutrient soil should be harvested before attack occurs.

Hastings et al. (1978) suggested maintaining tree vigor by: selecting species suited to the site, planting at desirable spacing, thinning to reduce competition, and removal, destruction or treatment of low-vigor or infested material. During thinning or harvesting operations, mechanical injury to residual trees should be avoided. Slash should be exposed to direct sunlight for rapid drying. Stacked pulp sticks or sawlogs should be removed within 3 weeks of cutting in summer.

In some cases, trap trees may be utilized in plantations where Ips activity is noted (Eiber et al. 1989). During a drought in Minnesota in 1981, trap trees were girdled to attract beetles, then removed in 2 weeks after adults had attacked. The process was repeated 2 weeks later to trap remaining beetles. Trap slash may be similarly utilized, if care is taken to remove and destroy infested material. Infested and potential brood material can be destroyed by burning, chipping, debarking, burying or piling under an airtight tarp (Eiber 1989).

A.1.15
Saratoga Spittlebug - Aphrophora saratognesis Fitch

Life Cycle
Saratoga spittlebug (SS) is a native, univoltine, sap-feeding insect. Primary hosts for SS are pines, particularly red pine and jack pine. Other conifers including white pine may be attacked intermittently, especially when mixed with red or jack pine. Red pine is the most preferred host and typically sustains the most severe damage. Jack pine is less-preferred, but may be seriously damaged in pure stands or when mixed with red pine. L.F. Wilson studied SS extensively and described many aspects of its ecology and management. Unless otherwise noted, the material below was extracted from Wilson (1987).

The SS life cycle requires two hosts. Adults feed on pines while nymphs feed on herbaceous alternate hosts. Hundreds of plant species may qualify as suitable alternate hosts for SS nymphs. However, sweetfern (Comptonia peregrina L.), a common understory plant in pine plantations, is the principle alternate host. Brambles (Rubus spp.), blueberry (Vaccinium spp.) and willow (Salix spp.) are also suitable hosts, although willow is seldom abundant in pine stands. Anderson (1947) and Linnane and Osgood (1976)

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examined the suitability of numerous plants for SS development. Many plants may act as interim hosts, supporting partial nymphal development. Nymphs may utilize one or more partial hosts when true alternate hosts are unavailable for all or part of the feeding period.

Adult SS may be present from mid-July through September. Eggs are laid throughout this period under bud scales (red pine) or in needle sheaths (jack pine). Eggs are most abundant in upper whorls; terminals may harbor 25% of the egg population. Eggs overwinter and nymphs first appear in May, when shoot elongation begins. Nymphs drop or are blown to the ground and immediately search for alternate host plants. Nymphs excrete liquid waste while feeding on plant juices. This waste is pumped with air, forming the characteristic spittlemass. The frothy spittlemass prevents desiccation and discourages natural enemies. One to three nymphs may occupy one spittle mass. Nymphs feed for 50-60 days, passing through five stadia.

Adult SS move to pines and feed on vegetative shoots. Adults prefer feeding on one-year old internodes in the upper canopy, but will feed on all needle-bearing shoots and the upper stem. Each adult makes 2-5 punctures a day through cortical tissue, down to the cambium of shoots and branches. Each feeding puncture results in a discolored patch (3.0-4.0 mm in diameter) of necrotic phloem and cambial tissue. Discolored streaks up to 3.6 cm long eventually appear. External damage may not be apparent, however, until foliage begins to wilt or shoots die and turn red (flagging).

Wilson (1987) developed a life table for 15 generations of SS observed in Michigan. Egg mortality ranged from 20-60% and was attributed to parasitism (0.1-12%), incomplete development, and unknown factors which likely included desiccation. Other workers have also observed egg parasitism of SS (Milliron 1947a, 1947b, Ewan 1961). No nymphal parasites have been recovered. Nymphal mortality of 8-63% was attributed to predation (small-moderate impact), disease (variable impact) and possible effects of late frost or desiccation. Adult mortality varied from 4-94% and resulted from a Dipteran parasite, disease, predation and other factors. Ewan (1961) recorded adult parasitism rates of 60% during an outbreak in Wisconsin.

Impact
Loss of plant juice combined with tissue necrosis diminishes the water conduction capacity of shoots attacked by SS. Scars from feeding punctures may interrupt water transport and cause moisture stress, particularly in the upper crown. This may be a particular concern on sandy sites, where soil water-holding capacity is low. Ewan (1961) related number of feeding scars to size of SS nymphal population and likelihood of shoot mortality and growth loss. Lightly attacked trees may show light branch flagging and volume loss, slight crooking and limbiness. Spittlebug control at this stage usually permits rapid response and recovery by damaged trees. Heavily damaged trees may sustain much greater volume loss. Feeding damage coalesces, blocking water transport and causing tree tops and upper branches

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to die. Heavy scarring on tree boles may result in compensatory growth on the other side of the bole and structurally weak wood. Adult feeding may also produce sweep or crook; such trees may break easily. Wilson (1987) suggested that two or more years of light-moderate feeding will generally reduce terminal and lateral shoot elongation. One to two years of moderate-heavy feeding results in wilted, yellowing foliage. Flagging, dead shoots and stunting may become obvious after two to three years of heavy feeding. Three or more years of heavy feeding can result in dead branches, crooked or misshapen trees, top-kill and tree mortality.

Tree height, stocking and number of whorls in the canopy can be used to estimate the number of "tree units" available for adult feeding (Wilson 1987). Potential growth loss was associated with 0.25-0.50 nymphs per tree unit. One to two nymphs per tree unit resulted in potential growth loss of 25-41%, along with flagging, top-kill and some mortality. Six nymphs per tree unit were associated with 66% growth loss potential, and extensive top-kill, mortality and degradation.

Stand vulnerability depends on tree size, leaf area and density. Plantation red pine between 2-15 ft tall are most frequently injured. Once crown closure occurs, sweetfern and other alternate hosts are shaded out. Large trees with higher leaf areas are less affected by cumulative SS feeding damage than smaller trees. High SS populations concentrated on a few stems in poorly-stocked stands may cause severe damage, particularly when infested trees have poorly developed crowns. Well-stocked stands where trees are 15 ft high or taller are not generally vulnerable to SS injury. Damage from SS may cause young red pine plantations to fail. Severely injured trees may produce low-grade products. Limbiness may prohibit use of trees for utility poles or pilings because of excessive knottiness (Heyd and Wilson 1981).

A significant impact of SS feeding may be transmission of disease pathogens. Feeding by SS is believed to vector burn blight virus to jack pine and can cause shoot, branch or tree mortality. Burn blight is only weakly pathogenic to red pine.

Contributing Factors
Density of alternate hosts determines whether a SS population will be able to increase sufficiently to cause serious damage (Kennedy and Wilson 1971). Occurrence of SS outbreaks is strongly related to the presence of sweetfern. Open areas scattered through the stand due to uneven planting, seedling mortality or rocky, unsuitable ground may be associated with an abundance of sweetfern or other alternate hosts (Ewan 1961). Sandy sites are most susceptible to SS population build-up and most vulnerable to SS injury. Sweetfern is well-suited to coarse, sandy soils where pines are often planted. Besides harboring SS nymphs, sweetfern competes strongly for water and may exacerbate tree stress during periodic droughts (Wittenkamp and Wilde 1964, Heyd et al. 1987). Ewan (1961) found SS outbreaks occurred in stands with 60 or more alternate hosts per milacre, but the presence of

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sweetfern increased the likelihood of epidemics. Kennedy and Wilson (1971) indicated 35-40% cover of sweetfern was required for population build-up, unless other woody alternate hosts comprised more than 50-80% of total cover.

Management and Control
Prospective sites for pine plantations should be risk-rated to identify probability of SS injury. Risk-rating involves determining the abundance of sweetfern and other alternative host plants relative to nonhosts. Risk-rating should be conducted between May and July to permit identification of alternate hosts. Low risk implies negligible injury from SS. Moderate risk indicates potential for light flagging on scattered shoots, some growth loss and a few crooked stems. High risk indicates potentially heavy growth loss, many crooked stems and numerous dead or top-killed trees. A rating of moderate or high risk suggests a need to consider economic costs and benefits associated with various management options. Strategies for dealing with moderate or high risk sites may include 1) accept SS risk and plant, 2) select an alternative planting site, 3) control sweetfern, or 4) monitor and control SS populations (Heyd and Wilson 1981). Heyd and Wilson (1981) provide comparisons of management alternatives for areas of different site quality and varying SS risk. Restriction of pine plantations to no-risk or low-risk areas may involve relocation of entire plantations or simply avoiding specific high-risk pockets within larger areas. Pockets with > 35% cover of sweetfern will likely sustain severe injury or require suppression. Avoiding high-risk pockets may enhance wildlife habitat in red pine plantations. Closely-spaced, vigorous trees will eventually shade out sweetfern. Cover provided by hardwoods in mixed stands may reduce abundance of alternate hosts (Secrest 1944).

Risk-rating is also appropriate for established stands where trees are less than 15 ft tall. Plantations should be risk-rated by early June. Nymphal surveys can then be implemented if required for control decisions. Moderate or high risk ratings indicate alternate hosts may require control or SS populations may need to be monitored and controlled. Treatment prescriptions for stands damaged beyond recovery should be bypassed. Risk-rating can be followed up by surveys to detect feeding injury, damage levels or presence of various SS life-stages. Methods to conduct SS population surveys are described by Wilson (1987) and Wilson and Hobrla (1987).

Herbicides provide the most effective method for control of sweetfern. Heyd et al. (1987) compared efficacy of herbicide treatments in Michigan plots where sweetfern accounted for 27-42% cover. Herbicide application reduced sweetfern cover to less than 3% in the year of application. Percent cover of sweetfern was less than 10% three years later, placing the site in the low-risk category. It should be noted, however, that a moratorium currently prevents herbicide application on National Forest land. Deep plowing can disrupt sweetfern regeneration, but also alters soil structure and water-holding capacity in sandy soils. Shallow plowing or mowing stimulates sweetfern

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growth unless repeated for two-three consecutive years, which is likely to be costly. Burning is not suitable for cultural control since sweetfern readily resprouts after fire (Heyd et al. 1987). Wilson (1971) suggests SS problems are less likely when red pine stands are well-stocked (6 x 6 ft spacing) and thinned when needed to promote vigor. Sweetfern cover should be reduced before trees are 3 ft tall.

Chemical insecticide applications for 1-3 years may be required to protect plantations in high risk areas where other methods of SS reduction are not feasible (Wilson 1971). Recognition of SS as a pest occurred concurrently with the development of DDT. Much early work related to SS focused on DDT application and efficacy (e.g. Secrest 1944, Anderson 1945, Milliron 1949). The quantity of DDT applied qualified SS as the most chemically treated forest pest on National Forest land in the northeastern U.S. during this period (Fowler et al. 1986). Other chemical control materials have also been evaluated (Wilson and Kennedy 1968, Wilson 1971). Chemical application should be timed to coincide with peak adult emergence.

Although egg and adult parasites may contribute to SS mortality, there have been no attempts to augment natural enemies. Biological control of sweetfern has been investigated but shows little promise to-date (Wilson 1987).

A.1.16
Pine Sawflies - (Hymenoptera: Driprionidae)

Several species of pine sawflies are found in Minnesota and most exhibit similar life history characteristics. Sawflies derive their name from the saw-like ovipositor that adult females use to cut slits and deposit eggs into needles. Caterpillar-like larvae feed on foliage, often colonially. Young larvae skeletonize needles, leaving midribs to dry out, fade and curl. Older larvae typically consume needles down to the base. Sawflies overwinter as eggs or pupae.

Most destructive pine sawflies belong to the family Diprionidae. Although extensive damage from pine sawflies is rare, defoliation can stress trees and occasionally cause mortality. Coincident populations of sawflies and other defoliators such as jack pine budworm may result in heavy or complete defoliation. Damage and control recommendations for pine sawflies common in Minnesota are briefly summarized below. Most of the following material, unless otherwise noted, was derived from Goulding et al. (1988). Other general references include USDA (1983), Martineau (1984), Coulson and Witter (1984), DNR (1985), and Drooz (1985).

Diprion similes (Hartig) - Introduced pine sawfly
This sawfly was introduced into North America in 1914. It feeds primarily on white pine, but red pines near infested white pine may also be infested. Unlike most other sawflies in Minnesota, D. similes has two generations per

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year. First generation adults emerge from cocoons in late April-June. Larvae hatch and feed through June-July on previous years needles. Young larvae are colonial but older larvae disperse and feed singly. Defoliation may, therefore, be more diffuse than that resulting from other sawflies. Second generation adults emerge from cocoons in August. Second generation larvae feed from late August to September on both new and old needles. Consumption and utilization of foliage from four pine species was investigated (Fogal 1977). Digestibility of foliage could be estimated from cellulose content of needles and feces (Fogal and Webb 1976). Utilization of dry matter and nitrogen by penultimate female larvae indicated jack pine foliage was nutritionally superior to foliage from red pine or white pine (Fogal and Kwain 1972).

Defoliation by D. similes can reduce growth rates of white pine. Severe defoliation can cause mortality. Red pines are rarely damaged severely.

Open stands of white pine are most vulnerable to D. similes damage. Red pines near infested white pine may be attacked.

Control of D. similes populations usually results from bird predation of cocoons, cocoon parasitism by introduced Hymenopterous wasps and cocoon mortality due to low winter temperatures (Coppel et al. 1974). Insect parasites of D. similes in Wisconsin were identified by Mertins and Coppel (1971). Hyperparasites rapidly adapted to introduced parasites; 11 species are associated with the primary parasite of D. similes (Mertins and Coppel 1973). Parasites of D. similes in Minnesota have been described (Thompson et al. 1977, Weber 1977). Pathogens may also contribute to population regulation. A fungus caused dramatic mortality of D. similes larvae in isolated areas in Wisconsin (Klein 1973, Klein and Coppel 1973).

Chemical composition of D. similes sex pheromones was determined, and pheromones were synthesized (Kikukawa et al. 1982), and tested in the field (Jewett et al. 1976, 1978, Olaifa et al. 1988). A mathematical model was developed to assess the feasibility of population suppression with pheromone traps (Mertins et al. 1975). Four generations of intensive trapping would theoretically eliminate the population from an isolated area.

When D. similes populations are present, defoliation, growth loss and mortality may fall within acceptable limits. Severe defoliation may require insecticide application. Early canopy closure should be promoted to prevent D. similes outbreaks. An insect growth regulator (diflubenzuron) prevented ecdysis and caused high mortality in laboratory tests (Fogal 1977, Fogal et al. 1979). Planting density should be 800 or more trees/ac. Survival of seedlings and saplings should be promoted through control of competing vegetation and rodents. If survival of seedlings is low, stands may require replanting or replacement of dead trees.

Neodiprion lecontei (Fitch) - Redheaded pine sawfly

N. lecontei attacks red and jack pine trees up to 20 ft in height. The sawflies overwinter in cocoons on the ground. Larvae hatch about late June and feed colonially for 5-6 weeks on old and then new needles. N. lecontei tolerated resin acids in new foliage which restricted related sawfly species to old foliage (Schuh and Benjamin 1984). Food consumption and utilization, and nutritive value of pine species was evaluated for N. lecontei and three other sawfly species (Fogal 1975). Fiber content may negatively affect approximate digestibility. Quantity of dry matter and nitrogen in the food were not related to any indices of food quality. Successful emergence of adults from cocoons may depend on relative humidity (Hawkins 1977). N. lecontei females release sex pheromones to attract males for mating. Chemical composition and use of sex pheromones of N. lecontei have been evaluated (Jewett et al. 1978, Matsumura et al. 1979, Kraemer et al. 1981). Natural enemies, temperature and inclement weather usually cause collapse of populations about 3 years after outbreaks begin. Rauf et al. (1979) observed 85% parasitization of N. lecontei eggs on red pine in Wisconsin.

N. lecontei periodically defoliate saplings and trees may die if heavily defoliated. Main shoots may be killed and lack of apical dominance may result in deformed stems. Hodson et al. (1982) found damage by N. lecontei and other insects reduced growth and stem form of jack pine. Incidence of attack varied among 30 Lake States provenances. Averill et al. (1982) suggested N. lecontei damage would be unlikely to affect future sawlog harvest on good sites since the least productive trees in a stand are usually affected.

Disturbed or eroded soil and soil less than 3 inches deep contribute to increased vulnerability of red pine. Red pine growing on poor sites or under stress may be less resistant to damage. Stands adjacent to northern hardwood stands (especially sugar maple), in frost pockets, or on areas with high water tables or low nutrient soil may be most susceptible. Drought stressed trees are preferentially attacked by N. lecontei (Averill et al. 1982). Competition from sweetfern, grasses, or bracken fern may increase water stress and lead to sawfly damage (Averill et al. 1982). Open stands are more susceptible to sawfly defoliation than dense or shaded stands.

When N. lecontei populations are present, some defoliation can be tolerated. Stands should be monitored to detect increasing populations. If infestations are light, larvae can be shaken or clipped off, or insecticides can be applied to selected spots. Aerial spray of a nuclear polyhidrosis virus (NPV), provided excellent control of pine plantations in Ontario, Michigan and Ontario (Kaupp and Cunningham 1977, Kaup et al. 1978, Groot and Cunningham 1983, Cunningham et al. 1986, Podgewaite et al. 1986). NPV application did not affect populations of nontarget organisms in Quebec (Kingsbury et al. 1978). Malathion application also provided excellent control on red pine in Michigan (Fowler et al. 1973). Other chemical

materials and formulations were investigated by Hopewell (1977). Large-scale outbreaks may require a broadcast application of a registered insecticide. To prevent N. lecontei damage, avoid planting red pine on shallow or disturbed soil or within 50 ft of northern hardwood stands. Control of competing vegetation may require mowing, tilling or herbicide application. Early canopy closure can be achieved by planting at high density (800 or trees/ac), controlling weed competition or rodents. In plantations with low survival, dead trees should be replaced or the entire stand should be replanted if necessary.

Neodiprion pratti banksiana (Rohwer) - Jack Pine Sawfly
Jack pine sawfly attacks jack pine and occasionally red pine near infested jack pine stands. Eggs overwinter and larvae hatch in May or June. Larvae feed colonially on previous year needles through early July. Colonial feeding behavior was shown to increase survival of young larvae by enhancing their ability to feed on tough needles (Ghent 1960). Larvae spin cocoons on the ground and pupate. Adults emerge in late August-September and lay eggs. Male response to sex pheromone components were examined by Olaifa et al. (1984). A virus disease and late spring frosts often contribute to mortality of high populations.

Older, open-grown trees are more susceptible to infestation than young trees or trees in closed stands. Even-aged stands and plantations are commonly infested. One episode of defoliation seldom causes mortality. Repeated defoliation may reduce tree vigor and growth. This sawfly was observed in 1985 in Minnesota feeding on declining shelterbelt trees and on trees along trails (Minnesota Department of Natural Resources 1978-1989). In 1989, 30-40 ac of jack pine, 30 ft tall, were moderately defoliated. Understory trees were heavily defoliated; both old and new foliage was consumed. Management recommendations are similar to those described for D. similes.

Neodiprion sertifer (Geoffroy) - European Pine Sawfly
N. sertifer was introduced to North America in 1925. It attacks red and jack pine up to 20 feet in height. Larvae hatch from eggs in mid-April to early May and feed preferentially on old needles. At high population densities, colonies may defoliate entire branches and will move to new hosts when trees are completely stripped. Investigations of feeding efficiency and utilization of food by larvae indicated larvae were adapted to low nitrogen food (Fogal 1975, Larsson and Tenow 1979). Larval mortality was not increased when Scots and red pine were fertilized with nitrogen (Fogal and Sullivan 1976). Larvae spin cocoons on the ground in July. Adults emerge and lay eggs in September-October. Chemical composition of N. sertifer sex pheromones and effectivenss of pheromone traps have been investigated in laboratory and field studies (Jewett et al. 1978, Kikukawa et al. 1983, Kraemer et al. 1983, Olaifa et al. 1987). Effects of mating frequency on fecundity and sex ratio were examined by Lyons (1976).

During outbreaks, N. sertifer mortality may result from starvation, parasitism, and cocoon predation by small rodents (Lyons 1964, 1977). A Hymenopterous larval parasite from Europe established in Canada, dispersed readily, and contributed to sawfly mortality (Griffiths and Lyons 1980). Establishment was successful in Wisconsin but parasitism rates were low (Schuh and Benjamin 1984). Cocoon predation by small mammals was a significant mortality factor in Scots pine plantations in Finland. Studies indicated N. sertifer outbreaks may occur on poor soils with little cover for small mammal predators or in northern areas where the cocoon period is short (Hanski and Parviainen 1985). Lyons and Sullivan (1974) found differential mortality between males and females arose from higher male mortality during egg and early larval stages, but increased predation of female late larvae and adults. Occurrence of differential mortality could affect sex ratio and estimation of effects of natural control.

Larval feeding may precede expansion of new foliage, usually allowing current year needles to develop normally. Larval feeding on new foliage may be inhibited by deterrent compounds in new needles (Niemela et al. 1981). Since trees are usually able to maintain at least sparse crowns, they generally are not directly killed. Heavy defoliation can decrease height and diameter growth by up to 80%. Overmature trees and trees weakened by repeated defoliation may be killed or attacked by other pests. Research by Fogal and Slansky (1985) showed larval frass was a significant part of litterfall and contributed significant amounts of nutrients to the forest floor. Defoliation of Scots pine induced changes in composition of cortical monoterpenes (Tobolski 1977), which could have implications for other pests.

Studies in Scots pine plantations indicated larval colonies were more frequent in less dense plantings; thus, open-grown trees are probably more susceptible to infestation than dense stands (Fogal and Slansky 1985). Canadian outbreaks usually occurred in previously infested stands where sawflies multiplied for a few years without regulation by natural enemies (Lyons 1977). Density of egg clusters tended to be related to tree height and trees on plantation edges had the greatest numbers of clusters (Wilson 1975). Sampling of N. sertifer populations may be affected by tree size and location within plantations. Outbreaks of N. sertifer in Sweden were associated with preceding drought, infertile soil, high between-tree competition and stand age of 20-40 years (Larsson and Tenow 1984).

If N. sertifer outbreaks occur, some defoliation and growth loss may be acceptable. Colonies of larvae on infested trees can be removed and destroyed. Insecticides can be used to spot-treat small infestations or broadcast sprayed on extensive infestations. A commercial virus is registered for use on N. sertifer larvae (Podgewaite et al. 1984). Manifestation of virus in larvae appears directly related to larval density (Kaupp 1983, Mohamed et al. 1985). Studies showed parasites treated with NPV could transfer the virus to feeding colonies (Mohammed et al. 1981). Early canopy closure and

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high survival of planted seedlings should be promoted as described previously.

Neodiprion nanulus nanulus (Schedl) - Red Pine Sawfly

N. nanulus feeds primarily on red and jack pine but will also attack white pine. Eggs overwinter and larvae hatch in May. Larvae feed colonially on old foliage, stripping a branch completely before moving to another. Prepupal larvae spin cocoons on the ground in July-August. Adults emerge in early fall and lay eggs. Sex pheromone compounds were identified and field-tested (Kraemer et al. 1983, Olaifa et al. 1987). Little tree mortality occurs initially since only old needles are consumed. Repeated defoliation can stress and cause mortality or attack by secondary pests. Open-grown trees and overmature trees are most susceptible. Damage by N. nanulus can be distinguished from N. sertifer by larval feeding habits. N. sertifer larvae eat entire needles; N. nanulus larvae leave inch long needle bases. Control and management recommendations are similar to those for N. sertifer, except that no virus is registered for use on N. nanulus. Insecticide application resulted in excellent control when edges of red pine plantations were treated with mist-blowers (Benjamin et al. 1984).

Neodiprion pinetum (Norton) - White Pine Sawfly

N. pinetum occurs on white pines, usually on trees up to 20 ft in height, and occasionally on red pine. Adults emerge in May-June and lay eggs. Sex pheromone components and influences on species recognition mechanisms were examined (Kraemer et al. 1979, Olaifa et al. 1988). Larvae hatch in late June to mid-July and feed colonially on old and then new needles. Whole branches and trees may be defoliated during the 5-6 week feeding period. Larvae spin cocoons in the soil, overwinter and pupate in the spring. Egg parasitism may be an important mortality factor. A Eulophid wasp parasitized 90% of eggs in Wisconsin in 1978 (Rauf et al. 1979). Defoliation usually results in reduced growth but severe attacks may kill seedlings or saplings. Localized outbreaks were frequent in Wisconsin and small areas of white pine were killed (Rauf and Benjamin 1980). Open stands are more susceptible to damage than closed stands. Control and management recommendations are similar to those described for D. similes.

Neodiprion swainei (Middleton) - Swaine Jack Pine Sawfly

This sawfly has been present in the Lake States since the early 1950's. Jack pine is the preferred host, but red and white pine may be attacked when adjacent to heavily infested stands of jack pine. N. swainei overwinters in cocoons, pupates the following spring and adults soon emerge. Sex pheromone compounds and male responses were evaluated (Jewett et al. 1978, Kraemer et al. 1984). Eggs are laid during June-July. Larvae are gregarious and feed on old foliage primarily. Lyons (1960) found larval aggregation was advantageous and increased survival. Larval feeding behavior is regulated by a gustatory response to inhibitory compounds in foliage in new foliage (Benjamin and All 1973). Larvae complete feeding in August and spin cocoons on the ground. Lyons (1977) reported that

populations tend to oscillate slowly and regularly. Patterns may be caused by fluctuations in natural enemies and the mid-point of population oscillations may drop sharply if insecticides are applied.

Outbreaks on Ontario and Quebec have occurred at roughly 8 year intervals. Foci of outbreaks were low vigor jack pine stands on outwash sand sites (McLeod 1970). Mortality began to occur within four years of population increase and high mortality occurred in overmature stands. Surviving trees in the outbreak area remained stag-headed for several years. McLeod (1979) developed a population simulation model for these vulnerable stands. Severe infestations in the Lake States have occurred in jack pine plantations and windbreaks. Studies in Quebec indicated application of a virus would provide control of N. swainei for at least one year (Smirnoff et al. 1962). No serious damage in Minnesota has been reported in annual insect reports dating back to 1978 (Minnesota Department of Natural Resources 1978-1989). Management recommendations are similar to those described for D. similes.

A.1.17
Pine Tussock Moth - Dasychira plagiata Walker

Outbreaks of pine tussock moth (PTM) have occurred at irregular intervals in northwest Wisconsin and east central Minnesota. Outbreaks have resulted in widespread defoliation of jack pine and red pine and tree mortality on occasion. Jack pine is preferred by PTM, but red pine is often attacked when adjacent to heavily infested stands of jack pine (Goulding et al. 1988). White pine, white spruce and tamarack may also be attacked in the Lake States.

Life History
Shreenivasam et al. (1972) conducted extensive studies of the bionomics of PTM in Wisconsin. Most of the following material in this section, unless otherwise noted, was derived from their report.

The PTM is a native, univoltine insect with a range extending into northeastern and east central Minnesota. Adult PTM emerge in late July-early August. Males are active fliers; gravid females are poor fliers. Oviposition occurs 2-3 days following emergence. Egg masses contain 25 eggs on average and are found on foliage or occasionally on twigs and bark. Larvae hatch in 8-12 days. First instar larvae may feed on egg shells for 24 hours, then begin mining current year needles. Larvae disperse and wander over bark and the tree bole for a variable period, then spin hibernaculae, molt and overwinter as second instars. Most overwintering occurs on the main stem, 9-13 feet aboveground, on stems 2.4-3.5 inches in diameter. Larval emergence begins in April and continues through May. Larval activity increases as temperatures reach 18° C. A second larval dispersal phase occurs as larvae migrate from overwintering sites on stems to foliage. Larvae preferentially feed on the previous seasons' foliage, but readily move

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to new needles when old foliage is depleted. Pupation occurs in mid- to late-July in cocoons on the underside of small branches and twigs. Larval setae are incorporated into cocoons giving them a hairy appearance.

Life tables were developed for two generations during a 1967-1969 outbreak. Mean fecundity of females averaged 231 and 214 eggs during the 2 study years. Egg mortality reduced populations by 56% and 21% in years 1 and 2 of the study, respectively. Mortality factors affecting eggs included parasitism, infertility, predation and unknown factors. Dispersal losses and parasitism caused considerable mortality to larvae. Predation, desiccation, and pathogens also reduced populations. Parasitism also caused significant mortality to pupae. Generation mortality exceeded 99% during the two years, reflecting the population collapse.

Parasites and pathogens, including fungi and a virus, demonstrated density-dependent responses to PTM populations. An earlier outbreak in 1922 in Wisconsin was apparently decimated by parasitism and disease (Fracker 1922). Thirty-one species of parasites were recorded from Wisconsin (Walgenbach 1965). Shreenivasam et al. (1972) presented tables listing parasites, predators and density/mortality relationships for the Wisconsin population.

Impact
Outbreaks typically erupt and collapse suddenly. One heavy defoliation can kill 25% of trees in infested stands and 50% of trees may be top-killed (Goulding et al. 1988). Stands may be destroyed if defoliation is heavy in 2 consecutive years (Goulding et al. 1988). A 1961 outbreak in Minnesota caused mortality to 100 ac of pole-sized jack pine (Bongberg 1962). Complete defoliation of 3500 ac of jack pine, red pine and white spruce at the General Andrews State Forest was also recorded. Eight-ten infestations have been observed in northwest Wisconsin since 1907. Peak defoliation occurred in 1961, when 60,000 ac of jack pine were defoliated. Outbreaks in Douglas and Bayfield counties (Wisconsin) tend to occur at 12-15 year intervals, but are rare outside this hazard area (Goulding et al. 1988). At the peak of an outbreak from 1967-1969 in Wisconsin, larval density was estimated to be ca 12.5 larvae per ft^2 of foliage (Shreenivasam et al. 1972). An economic threshold of 7 or more egg masses per tree was identified by the Minnesota Department of Natural Resources. Major outbreaks have occurred where 1000 ac pockets spread to 40,000-60,000 ac infestations within 2 years (Goulding et al 1988). Red pine usually sustains damage only when it occurs near large blocks (e.g. > 600 ac) of jack pine (Goulding et al. 1988).

Annual Insect and Disease Reports of the Minnesota Department of Natural Resources indicate PTM populations began increasing near Brainerd and in Pine county in 1978. Defoliation of 360 ac in General Andrews State Forest occurred in 1979. Populations continued to grow in 1980 in Crow Wing county. Extensive defoliation and top-kill was expected. Aerial sprays were

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conducted in selected areas to protect seed orchards, nurseries, windbreaks and some plantations. Officials felt allowable cut levels would not absorb potential salvage operations or resulting lags in softwood production. Populations were concentrated in young pine plantations and non-commercial jack pine stands. In 1981, the population collapsed. The collapse was attributed to high numbers of diseased larvae, probably a result of warm, moist weather during the feeding period. Since 1981, PTM populations have remained low. Pheromone trapping, along with larval and egg mass surveys, has been instituted to locate and monitor populations. Although high trap catches were occasionally recorded, defoliation has been minimal in recent years.

Management and Control

Goulding et al. (1988) described management alternatives for PTM in Wisconsin in the event of an outbreak. One alternative is to accept some defoliation and monitor stands for unacceptable damage levels. Methods used for population surveys of PTM in Wisconsin are presented by Shreenivasam et al. (1972). Treatment of small infestations in year 1 of an outbreak may prevent expansion of the outbreak. Chemical or microbial insecticides can be applied to jack pine stands threatened with severe defoliation. PTM populations were suppressed with DDT until 1964. Several other materials, formulations and application methods were evaluated in Wisconsin (Shreenivasam et al. 1972). Bt or other registered insecticides may be applied in spring to control emerging larvae and protect foliage (Benyus 1983). Applications in early- to mid-August may control emerging larvae. Heavily defoliated stands should be harvested if feasible. Red pine can be protected by removing adjacent infested jack pine stands. Methods to prevent buildup of damaging PTM populations revolve around reduction of large, continuous stands of jack pine. Goulding et al. (1988) suggest breaking up large stands of jack pine by converting to red pine. Jack pine should comprise no more than 30% of the total vegetation in a township area. If site index is 55 or less, jack pine stands should be harvested at 40-45 years of age. If site index is 60 or more, jack pine can be harvested at an age equal to site index value minus 5. In addition, managers should avoid establishing jack pine in townships where more than 40% of the vegetation is jack pine type. Jack pine stands should be less than one square mile.

A.1.18
White Grubs - Phyllophaga spp. and Serica spp.

The following information was extracted from Anonymous (1991), Fowler and Wilson (1971), Speers (1961), and Sutton and Stone (1974).

Life cycle

White grubs are soil-inhabiting Scarabaeid beetle larvae that feed on roots of conifer seedlings and other trees. Two genera, Phyllophaga spp. and Serica spp. are primarily responsible for damage in Minnesota. Phyllophaga spp. is most common and has a life cycle of 3-5 years. Serica spp. are smaller

and live 2-3 years. Adults emerge from soil in spring and feed and mate nocturnally on hardwood trees and shrubs. Adults return to the soil in the day. Females lay eggs in the ground. Larvae hatch and feed on roots and organic matter, typically for ca 3 years. Pupation occurs in mid-summer. Generations frequently overlap during the three year life cycle. Adults and larvae overwinter in soil. Second-year grub larvae tend to feed more voraciously than first-year larvae. Feeding in the third year stops in mid-summer when larvae pupate.

Impact
Grubs feed 1-3 inches deep and cut off roots growing horizontally. First-year grubs feed mainly on fine roots, but thereafter consume the entire root system. Grubs will attack all tree species, but conifers, especially pines, are preferentially attacked and recover from damage slowly. Heavy damage generally occurs at three-year intervals, but rarely in two consecutive years. Feeding by grubs frequently causes seedling mortality. Height growth of spruce seedlings that survived attack was reduced even though new rootlets were regenerated. Surveys of one cubic foot of soil have been related to percent of trees damaged in Minnesota plantations. An average of 1/2 grub/ft^3 in preplant surveys is indicative of 16-34% mortality two years after planting. Allowable losses of 20% or less correspond to 1/4 grub/ft^3.

Contributing factors
Grubs move through soil in response to moisture and temperature. Prolonged drought may cause high grub mortality. However, drought may increase seedling water stress, contributing to grub impact. Soil fertility, moisture and rooting depth determine the ability of attacked seedlings to survive and the availability of food for grubs. Grub problems are most severe on sandy to sandy-loams and minor on heavy, clayey soils. Plantations established in fields previously covered with sod two or more years are most susceptible. The proximity of hardwood trees that provide adult food may affect grub population levels. Populations are substantially reduced if adults must fly beyond 100 yds.

Management and Control
Pre-plant surveys should be conducted to asses grub populations. Planting in years of high grub populations or where dense populations are present should be avoided. Damage can be reduced by avoiding sites within 100 yds of hardwoods. Pre-plant insecticide controls may be used, depending on registration and availability of compounds. No chemical control options are available after planting.

A.1.19
Northern Hardwood Bud-Mining Complex

A complex of bud-mining insects may affect quality of some northern hardwood species. However, limited information on the biology and impact

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of these insects is available. Miller et al. (1978) evaluted growing stock quality and defects of trees in northern hardwood stands in Wisconsin and Michigan. Study plots were generally dominated by sugar maple, with basswood, red maple, yellow birch and various minor species also present. After examining interior defects of more than 400 dissected stems and exterior defects of over 2,000 trees, the authors concluded that the majority of trees were of very poor quality. Branchiness-forkedness was identified as the most common defect, affecting 52 to 87 percent of all species. Nearly 70 percent of sugar maple trees 4 to 15 inches in diamater had the branchiness-forkedness defect. Miller et al. (1978) noted, however, that the branchiness defect in sugar maple increased up to the 10-inch size class, but then stabilized or decreased in larger trees. The branchiness defect may therefore impact pulpwood harvests more than sawlog harvests.

Miller et al. (1978) observed evidence of the bud miners Proteoteras moffatiana and Obrussa ochrefasciella on dissected stems of sugar maple. Feeding by these insects appeared to destroy terminals, resulting in disruption of apical dominance and increased branchiness and forkedness in stems. Other bud-mining insects, including Rudebecia urticana, Epinotia solicitana, and Spilonota ocellana, were found boring in terminals of other northern hardwood species. Injuries to terminals resulting from these insects appeared to be similar to injuries observed in sugar maple.

Relatively little is known about the life history of these insects. In general, the insects are univoltine. Proteoteras moffatiana larvae enter the mine terminal buds in late summer, overwinter, then mine additional buds in spring before shoot elongation is completed. No management or mitigation studies related to these insects have been reported.

A.2
FOREST INSECTS AND POLLUTANTS

Introduction
Interactions between forest insects and air pollutants may have implications for forest health and productivity in the future. Long-lived forest trees may suffer chronic exposure to pollutants or experience repeated exposure to acute levels of contaminants. Although mechanisms are not well understood, exposure to pollution can affect many aspects of tree physiology. Changes in biochemistry, allocation or other processes may occur well before symptoms of pollution exposure are detected. Pollution may affect insects via three major pathways: 1) gases, acid rain or deposited toxins may directly impact insects, 2) pollution may affect relations between herbivores and their natural enemies, and 3) suitability of host plants may be altered (Riemer and Whittaker 1989). In addition, pollution may also affect insect microclimate or microhabitat, or impact entire insect communities by altering abundance or distribution of plants (Hughes 1988).

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Several reviews of interactions of pollution, plants and insects have been recently published and were acquired for this review. Alstad and Edmunds (1982) surveyed literature prior to 1982 and focused on effects of specific compounds on various insect species. They also discussed the lack of available experimental data and the need to distinguish correlation from causal mechanisms. Fuhrer (1985) focused on air pollution as a superordinate factor in forest ecosystems, affecting environmental variables, plants, herbivores and entomophagous organisms. Baltensweiler (1985) discussed European observations on relations between Waldsterben, bark beetles and defoliators. Hughes (1988) described various pollutants and reviewed both experimental and correlative studies of pollution effects on plants and herbivorous insects. He also discussed experimental approaches for investigating cause and effect relationships and mechanisms of pollution induced change in plant-insect interactions. Riemer and Whittaker (1989) extensively reviewed relations between air pollutants and insects, including field observations, studies along pollution gradients and direct experimentation. Mattson and Witter (1990) reviewed potential effects of pollution on host plant quality and subsequent indirect effects on herbivores and entomophagous insects. They identified five pollution scenarios and hypothetical effects on forest ecosystem structure and stability. These reviews and other literature pertaining to relations between forest insects and pollutants are briefly summarized in this report. Pollutants considered in this report include air pollutants such as ozone, nitrous or sulphurous oxides, and acidic deposition. The discussion is directed at general impacts of pollutants on forest insects. Readers should consider reviews by Alstad et al. (1982), Hughes (1985) and references therein for more information on specific pollutant compounds.

General relations between pollution and forest insects
Field observations and studies along pollution gradients suggest pollution may cause changes in insect abundance and species composition. Increased populations of sucking insects such as aphids, shoot borers and other internal feeders, some bark beetle species and some leaf feeders have been reported in pollution affected areas (Baltensweiler 1985, Fuhrer 1985, Hughes 1988, Reimer and Whittaker 1989). Since the 1970's, outbreaks of novel Lepidopteran or Hymenopteran defoliator species have been reported from areas near pollution sources or areas exposed to acidic deposition. Many of these insects were not previously considered pests (Riemer and Whittaker 1989).

Relations between insect population levels and pollutants is unlikely to be linear (Riemer and Whittaker 1989, Mattson and Witter 1990). Insect populations and pollution levels may be negatively correlated at high pollution levels, but positively correlated at moderate to low levels. Fuhrer (1985) hypothesized that insects could be grouped into three classes based on their response to pollution. One class of insects either tolerate or escape heavy contamination, benefit from pollution induced tree stress and elimination of sensitive natural enemies. Aphids, shoot borers, and other

insects abundant near pollution point sources may fall into this category. A second class includes insects absent from pollution centers but abundant at low to moderate pollution levels. This class may include some bark beetles and defoliators with moderate pollution tolerance or escape habits, who benefit from pollution induced plant stress and elimination of sensitive natural enemies. The third class includes insects that are highly sensitive to contaminants or to host plant changes induced by pollution. These insects normally would proliferate on stressed hosts, but are conspicuously absent from pollution affected areas.

Knowledge of relations between pollutants and forest insects is growing, but direct quantifiable evidence linking pollutants to insect abundance or performance is rare. Although observational and correlative studies are important, they do not indicate whether pollution impacts insects directly or through changes in natural enemy populations or host quality. Identification of causal mechanisms is likely to be difficult and involve complex interactions among pollution compounds, environmental variables, tree and insect physiology and third tropic level organisms.

Direct effects of pollutants
Pollutants may directly affect phytophagous insects by altering survival, growth, fecundity or other aspects related to their physical capacity. Direct effects of pollutants on insects may depend on the physiological ability of the insect to tolerate contaminants, or a life-style that permits insects to avoid heavy contamination (Fuhrer 1985). Fuhrer (1985) speculated that mobile insects may be more exposed to contaminants than sessile insects. Thus, sap-sucking insects may be less exposed than leaf-feeders and entomophagous insects may be most exposed. External feeders are likely to encounter more pollutants at higher concentrations than sap-suckers, which will encounter only those compounds that penetrate plant tissue. Endophytic species, such as bud or shoot borers, leaf miners, or gall-inhabiting insects may be protected from external contaminants throughout most of their life cycle.

Riemer and Whittaker (1989) exhaustively reviewed studies of pollutant effects on insects. Their review of field observations dating from the early 1800's indicated conflicting responses of forest pests to air pollution. Aphids and other sap-suckers and shoot borers often, but not always, increased with pollution levels. Increased attack of ozone-damaged conifers by bark beetles was frequently reported and presumably relates to changes in host-tree resistance. However, industrial pollution may have direct negative effects on survival and fecundity of some bark beetle species (Fuhrer 1985). Conflicting results of field observations were also reported for various Lepidopteran defoliators. Experimental studies of direct effects of pollutants on defoliators are scarce. An increase in reports of widespread changes in insect herbivory and an increase in damage by previously endemic, "non-pest" defoliators has been noted by several authors (Baltensweiler 1985, Riemer and Whittaker 1989). Riemer and Whittaker (1989) suggested such reports may relate to "high stack" policies, resulting in dispersion of

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pollutants over a wider area around a point source, along with an increased awareness of herbivory.

Effects of specific compounds on insects were reviewed by Alstad et al. (1982) and Fuhrer (1985). Direct primary effects of ozone, flourides, and heavy metals, sulphurous compounds and mixed industrial pollution were generally detrimental to various insects. In most cases, observations of insect abundance and distribution in the field corresponded to pollutant gradients. Experimental confirmation of field observations and an understanding of toxicity mechanisms were generally not available, however. Riemer and Whittaker (1989) reviewed the scattered experimental data acquired in studies of direct effects of pollutants on insects. They concluded that sensitivity to pollutants is highly variable among species and that pollutants could affect changes in insect community structure. They also noted the lack of data related to questions such as bioaccumulation of toxic pollutants in entomophagous insects, interaction of pollutants and microclimatic variables and effects of combinations of pollutants.

Pollution and natural enemies
Dense populations of herbivorous insects in polluted areas may indicate a release from control exerted by predators, parasites or pathogens. Equilibria established between insect herbivores and natural enemies may be disrupted by pollution-induced changes in insect development rate, searching ability of predators or parasites, and other behavioral and physiological factors (Alstad et al. 1982). Field observations have suggested high populations of aphids, Lepidopteran and Hymenopteran defoliators were often correlated with reduced parasitism rates in polluted zones (Reimer and Whittaker 1989). Fumigation with SO_2 directly reduced parasitism rate or abundance of parasitic species in two studies reviewed by Riemer and Whittaker (1989). Predators appear to respond similarly; abundance and species diversity of entomophagous arthropods appear to be negatively correlated with pollutant gradients. Braun and Fluckiger (1984) experimentally showed aphid predation was lower near a highway than away from the highway. Price et al. (1974) observed trophic amplification of lead originally accumulated in roadside plants.

Pollution and host suitability
Pollution induced changes in plant biochemistry may affect the nutritional value of plants or the ability of herbivores to utilize host plants. Acidic deposition, for example, can leach nutrients from foliage, alter soil pH, affect nutrient cycling and availability of nutrients to plants, and may be detrimental to biological nitrogen fixation and mycorrhizal associations (Hughes 1988). Nutrient concentration or nutrient balance within plant tissue may subsequently change, indirectly impacting herbivorous insects. Nitrogen, a critical nutrient for folivores, may increase in response to acidic deposition or gaseous pollution, potentially enhancing performance of many insects (Mattson and Scriber 1987). Riemer and Whittaker (1989) concluded soluble amino acids generally increase in response to pollution. Increased

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levels of glutathione resulting from exposure to SO_2 were shown experimentally to stimulate insect feeding and growth (Hughes and Voland 1988). Pollution frequently alters carbohydrate metabolism in plants; carbohydrates may affect insect feeding rates and utilization of host foliage (Reimer and Whittaker 1989). Pollution may also affect levels of water, minerals, salts, vitamins and sterols in plants, which could then impact insects (Riemer and Whittaker 1989), but few data are available that address these topics.

Success of herbivorous insects is also dependent on secondary compounds in plants, and interactions of these allelochemics with nutrients. Various studies have indicated pollution may affect terpene metabolism in conifers and suitability of trees for folivores or bark beetles (e.g. Cobb et al. 1968, Stark and Cobb 1969, Lechtio 1981). Changes in terpene production due to pollution may affect generalist and specialist herbivores differently, and could alter composition of herbivore fauna (Reimer and Whittaker 1989). Phenolic metabolism may also react to pollution. Riemer and Whittaker (1989) reviewed several studies where phenolics increased or decreased after exposure to pollutants. Other allelochemics such as alkaloids are also known to affect insect herbivores, but have not been related to pollution.

Mattson and Witter (1990) identified five potential scenarios that could result from alterations in quantity or quality of plant tissue due to pollution. Decreased levels of plant nutrients, along with nutrient dilution or diminished plant growth would likely reduce long-term success of most herbivorous insects, although aphids and similar sap-suckers may proliferate. Moderate elevations in plant tissue nutrients may benefit herbivores directly and could lower efficacy of natural enemies. Plants may be more able to tolerate or compensate for damage. Substantial elevations in nutrient levels may result in physiological dysfunction in plants. These plants could be highly suitable for insects, at least temporarily. This scenario could lead to unstable systems and episodic pest outbreaks. Effects of pollution may also alter ecosystem structure and function (Mattson and Witter 1990). Chronic and substantial changes in nutrient availability and plant tissue nutrients may lead to replacement of existing plant species with species more suited or tolerant of nutrient regime. Reduced ecosystem structure and diversity may result in loss of herbivore natural enemies or their habitat, leading to enhanced success of pollution tolerant herbivores. Fajer et al. (1980) suggested enhanced CO_2 concentration could reduce host plant quality and subsequent herbivore load. However, insects that survive or adjust to lower foliage quality may consume more foliage, negating any benefits to plants from reduced herbivore load.

Summary
Pollution is likely to profoundly affect many aspects of ecosystem structure and function. Effects of pollution on forest insects may be substantial, but are not well understood. Existing evidence from observational and correlative studies suggests proliferation or enhanced success of many forest

pests may be associated with pollution. Effects may be due to reduced impact of natural enemies, altered host suitability, decreased host resistance or other factors. Aphid problems seem likely to increase in polluted areas, but impacts on other forest insects appear variable and species-specific. Few studies have shown cause and effect relations between pollution and pest populations or identified mechanisms underlying pest response to pollution. Interactions between plants, insects and pollutants are likely to be complex, especially when pollution involves mixtures of compounds.

A.3
RESEARCH NEEDS

A significant product of the technical review process was identification of knowledge gaps that preclude confident prediction of pest impact, delineation of factors contributing to pest problems, and determination of appropriate mitigation strategies. Many of the knowledge gaps pertinent to specific insect pests are identified in the body of the technical review. Generalized areas requiring further research are briefly summarized below.

Knowledge of impacts of forest insects on tree growth and mortality varies widely. In most cases, impact is heavily affected by site-related factors. Increased knowledge of how environmental factors and management activities affect insect damage is needed before impact can be predicted or modelled for most species. Effects of insects on reproduction and non-timber resources such as aesthetics, wildlife and recreation, are poorly known.

Long-term impacts of forest insects are not well known. Outbreaks of forest pests typically result in mortality and growth loss during the outbreak and for a few years after outbreaks subside. In a few cases, however, long-term studies indicated decreased competition among residual trees for light, water, nutrients and space could boost overall productivity. Little is known about long-term, net effects of Lake States insects, especially defoliators, on stand productivity. Federal or state agencies are probably best situated for long-term data collection, but consistent funding and direction will be required.

In some cases, experimental work has identified silvicultural strategies to reduce impact of insect pest outbreaks. Designed implementation of such experimental strategies over a range of site conditions, combined with long-term survey and data collection, would greatly enhance our understanding of how susceptibility and vulnerability to pests can be addressed through management.

Weather is likely a critical factor affecting frequency, duration and severity of insect outbreaks. Relations among weather variables, pest problems and pest impact are difficult to study and are not well understood. Development of new tools such as geographic information systems may increase our ability to study effects of weather on insect pests. However, the lack of long-term

pest data, particularly of endemic populations, could undermine efforts to assess weather and pest relations.

More knowledge is needed on mechanisms by which trees resist insect attack and tolerate damage. Biochemical processes and patterns of resource allocation contribute to resistance, but mechanisms must be identified. Effects of environmental variables, including drought, on resistance mechanisms are not well-understood. Data related to root systems are particularly poor. Identification of genetically based resistance mechanisms could contribute to selective breeding and management activities to enhance natural resistance.

Entomophagous insects and pathogens contribute significantly to mortality of many insect pests and prevent other insect species from attaining pest status. Very little information is available on habitat requirements of predaceous or parasitic insects, and how silvicultural activities may affect entomophagous populations. More research is also needed on endemic populations of pest insects between outbreaks to determine what factors control populations and contribute to pest population release and outbreaks.

Other organisms including birds, small and large mammals, reptiles and amphibians may feed consistently or opportunistically on forest insects, including pest and non-pest species. Potential impacts of forest pest management tactics, including silvicultural manipulations, on non-target organisms and interspecific linkages among higher organisms are not well known.

We generally have poor knowledge of the diversity and structure of insect communities in Lake States forests. This type of baseline knowledge is needed to assess impacts of silvicultural or mitigation treatments, as well as pest insect outbreaks, on other herbivores, decomposers and entomophagous insects. Our lack of knowledge of insect abundance and diversity contributes to the difficulty of assessing impacts of management activities on other organisms that depend, directly or indirectly, on insects as a food source.

APPENDIX B.

REVIEW OF THE LITERATURE --

FOREST DISEASES

Prepared by

Jane Cummings Carlson

Forest Pathologist

B.1
Aspen - Birch

B.1.1
White Trunk Rot of Aspen - *Phellinus tremulae*

White trunk rot caused by *Phellinus tremulae*, has been recognized since 1909 as the major cause of decay of aspen in North America (Schrenk and Spalding 1909) and has been reported as the primary cause of heartrot of aspen in Minnesota (Schmitz and Jackson 1927). It causes more wood volume loss in aspen than any other diseases. *P. tremulae* is a wound parasite so trees with branch stubs, broken tops, cankers, fire scars, and other stem wounds are likely to have extensive heart rot. A relationship between age of aspen and amount of rot has been reported (Basham 1958). Basham showed that the percentage of trees with rot in the merchantable portion of the bole increased steadily from 26.7 percent in stands 41 to 60 years old to 100 percent in stands 161 to 180 years old. Schmitz showed that when the volume of decayed wood is deducted, the mean annual growth of well stocked aspen stands on average sites culminates between 40 and 50 years. This Minnesota study indicates that if aspen is grown with protection from fire on a 40- to 50-year rotation, decay will not be a very serious factor in its production. Other methods that reduce the incidence and severity of decay include: 1) protecting the trees from fire and minimizing wounding, 2) maintaining well-stocked stands to encourage natural pruning thus reducing infection courts and, 3) removing infected trees when conducting improvement cuttings (only used with non-clearcut systems) (Ohman and Kessler 1964).

There is conflicting information on the relationship between site and disease incidence. Basham showed that aspen stands on deep, sandy silts or loams, or on shallow sandy loams over impervious clay, had less decay than aspen on drier sites (slightly silty or fine pervious sands, silty or loamy sands over pervious sands or coarse material) or wetter sites (deep silty loams and clays or sandy loams over somewhat impervious clay). A negative correlation between site quality and decay has also been suggested (Brown 1934).

Variation in volume of decay among different aspen clones has been demonstrated (Wall 1971). These clonal variations may affect the relationship between site and decay and clone may have a greater effect than site on decay incidence.

Harvesting Implications
Any harvesting that reduced the number of acres of aspen over 50 years old, would very likely reduce the incidence of decay caused by *P. tremulae*.

B.1.2
Hypoxylon Canker of Aspen - *Hypoxylon mammatum*

Hypoxylon canker is a serious disease of aspen in eastern North America. In Minnesota, Wisconsin, and Michigan, losses due to Hypoxylon canker are estimated to be $4 million annually, and in 1971, the average proportion of live aspen trees infected was 12.1 percent (Marty 1972). This fungus disease is primarily a pathogen of quaking aspen; bigtooth aspen is occasionally infected, and infection of balsam poplar is rare.

Aspen in all age classes are susceptible to infection. Mortality, however, is usually greater in young trees because the cankers occur lower on the stem and the trees are girdled. High-vigor and low-vigor trees are susceptible to infection (Anderson and Anderson 1968). The disease organism is a wound parasite (Gruenhagen 1945). Recent work has shown that insect wounds may act as infection sites for Hypoxylon (Anderson and others 1979). The prevalence of infection in the Lake States varies with geographic location, with the lowest levels in northern Minnesota and the highest in parts of Wisconsin and the Upper Peninsula of Michigan (Anderson 1964). Anderson also showed that more trees are infected along stand edges than within stands.

Canker incidence and host density are correlated; low-density stands have proportionally more infection than high-density stands (Anderson and Anderson 1968). Anderson's study in northern Minnesota showed that stands thinned to between 610 to 890 stems per acre had 23.6 percent of the trees killed by Hypoxylon, 15 years after thinning. In contrast, unthinned stands with between 1,400 to 4,210 stems per acre had 14.4 percent of the trees killed by Hypoxylon in the same amount of time.

Management of aspen to minimize Hypoxylon as summarized by Ostry (1981) includes the following:

1. Susceptibility to infection varies by clone; therefore, it is important to favor superior clones that are resistant to the disease and eliminate the susceptible ones (Perala 1977). If highly susceptible clones cannot be replaced, it may be necessary to convert to other species to obtain full production from a site.

2. Thinning favors Hypoxylon so this management strategy should only be used in stands with low levels of the disease. Trees with stem cankers will not live to rotation and should be removed.

3. Management practices that encourage good reproduction should be used. Understocked stands too young to be harvested should be regenerated to obtain full stocking. If nothing is done, these stands will be susceptible to attack by insects and Hypoxylon that together may cause the stand to breakup prematurely.

Harvesting Implications

Harvesting can reduce disease incidence under the following situations:

1. If 15 to 25 percent of the aspen trees are infected with Hypoxylon, and the stand is clearcut and the site treated to encourage good aspen reproduction.

2. If more than 25 percent of the trees are infected, and the stand is harvested and converted to other species.

3. If thinning is done in a fully stocked stand with very low levels of disease, and the infected trees are removed during thinning.

B.1.3
Armillaria Root Rot of Aspen - *Armillaria* spp.

Armillaria is an important root-rotting fungus (Shaw and Kile 1991). Root rot caused by *Armillaria* has been reported in aspen suckers produced after clearcutting of mature stands (Basham 1988, Gross and Basham 1981, Otoide 1976). In studies in northern Wisconsin, root rot incidence increased with stand age, with >70% of the sampled trees having infected root systems in 15-year old stands (Stanosz 1987a). Both the numbers of infected trees and the numbers of lesions per infected tree were greater as the interval after cutting increased. It is unknown what rotation age is best for minimizing the long-term impact of Armillaria.

Stanosz also studied the effects of short rotations on the incidence of Armillaria in roots of aspen sprouts in Minnesota and Ontario (Stanosz 1987b). He found that at the end of four 4-year rotations in Minnesota, or three 5-year rotations in Ontario, the number of stems harvested was only a fraction of the number present at the end of the first short rotation. Armillaria root rot occurred most frequently in the Minnesota plot where 12 of 18 suckers and 11 of 12 stump or root collar sprouts were infected; this translates to 77 percent of the sprouts being infected. Biomass yields in the last harvests at both locations were less than 20 percent of those from the first rotation. When 8 year rotations were used, the harvest from the third rotation was predicted to be less than one-half that of the first. Also, in Ontario, the numbers and sizes of suckers and sprouts from stumps and root collars produced after one 13-year rotation were so low that significant decreases in yields were expected.

Physical disturbance of the soil by logging or scarification has been shown to increase the amount of Armillaria inoculum and increase the chance of infection (Redfern 1973, Basham 1988). Inoculum is increased when Armillaria rhizomorph networks are severed during soil disturbance and new networks are formed from the severed pieces. The chance of infection is increased both by an increase in inoculum and an increase in the number of wounds on the root systems.

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Partial cutting has also been shown to increase Armillaria root rot (Edgar and others 1976, Filip and Goheen 1982). Trees are often stressed upon release by sunscald, winter injuries, wind stress, changed water tables, and increased soil temperatures which can predispose them to Armillaria root disease. The weakened trees may also be surrounded by stumps which act as food bases for the root rot.

Harvesting Implications
It is unknown exactly what harvesting prescriptions (rotation age, and how many rotations) for clearcuts or partial cuttings will minimize Armillaria root rot. It is known that root rot incidence can increase as a function of stand age, and that biomass can be reduced after repeated short rotations. Armillaria root rot may limit rotation length and the number of times aspen stands can be successfully vegetatively regenerated.

B.2
Black Spruce

B.2.1
Eastern Dwarf Mistletoe - *Arceuthobium pusillum*

Dwarf mistletoe is a parasitic seed plant that causes growth reduction, reduced seed production, wind breakage, predisposition to insects and decay, and mortality of black spruce. In Minnesota, the incidence of eastern dwarf mistletoe has been estimated at as much as 11 percent, which would involve approximately 154,000 acres of commercial black spruce type (Anderson and Kaufert 1953).

In recent Minnesota Department of Natural Resources pest surveys, black spruce in Koochiching County was evaluated for eastern dwarf mistletoe. Twenty-one percent of all the black spruce acres were found to be infected to various degrees (MN Forest Pest Report 1987).

Each dwarf mistletoe fruit contains a single viscous-coated seed that is explosively expelled from the fruit and propelled up to 15.2 meters where they may land and adhere to uninfected needles. Some of the seeds slide down to the twigs where infection occurs. The average annual outward spread of the parasite from an infection center to surrounding healthy trees is 0.5 to 3 meters. Spread is faster in unevenaged stands than in even-aged stands because infected overstory trees disperse seeds to understory trees over a larger radius.

The most practical method of reducing the incidence of eastern dwarf mistletoe is to clearcut infected stands and eliminate latent and undetected infections in residuals through prescribed burning (Irving and French 1971). In 1961-1966, a study was conducted in northern Minnesota to determine if clearcutting black spruce with a special effort to remove all black spruce in the clearcut and all trees in an area one chain beyond the infection center

would be enough to eradicate disease (French and others 1968). French found that a large number of trees were missed during the clearcut and concluded that it is difficult and probably impractical to remove all the black spruce.

Harvesting guidelines as proposed by Johnston (1977) and Ostry and Nicholls (1979) are as follows:

1. Reproduce and maintain dense stands because infection spreads more slowly and causes less damage in them than in open stands.

2. Clearcut infected stands plus a surrounding strip a minimum of 1 chain wide. Cut or otherwise kill all residual trees in the clearcut, especially those 1.5 meters or taller. Residual trees could carry the infection into the regenerated stand. Where possible, broadcast burn slash.

3. On the best sites, examine stands that have been cut within the last 10 years for the presence of infected residual trees. These trees should be cut or killed to prevent infection of the regeneration.

4. Establish timber sale boundaries to include mistletoe pockets.

5. Locate landings in mistletoe pockets.

6. Clearcut pockets of mistletoe plus a 1- to 2-chain-wide strip around the pocket in immature stands. These pockets should be controlled because they gradually enlarge and are a source of inoculum.

Harvesting Implications
Increasing the area of clearcuts in black spruce should reduce disease incidence if areas with eastern dwarf mistletoe are cut. It is important that residual black spruce is removed or destroyed and the stand be revisited for evaluation of infection levels ten years after a clear cut. Uneven-aged management should not be practiced with black spruce if disease management is desired.

B.3
Lowland Conifers

For significant diseases of balsam fir, refer to spruce-fir section. No other diseases of lowland conifers are discussed as their incidence is either unknown or of little consequence.

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B.4
Lowland Hardwoods

B.4.1
Dutch Elm Disease of American Elm - *Ophiostoma ulmi*

Dutch elm disease was first detected in Minnesota in 1961 and is now widespread throughout the state (MN Forest Pest Report 1981). Methods for intensively managing Dutch elm disease are well documented (Hanisch and others 1983) and are used primarily in the urban areas because of the high cost of managing this pest.

Overland spread of this disease occurs via the native and European elm bark beetles. The European elm bark beetle overwinters as a larva just beneath the bark of recently dead or weakened elm wood (brood wood). Adult beetles emerge from the wood about mid-May and continue to emerge throughout the warm months. The native elm bark beetle will either overwinter as a larva in infected trees or will emerge from the brood wood in the fall and spend the winter as an adult in shallow channels burrowed into the bark of healthy trees.

In the forests of Minnesota, prompt removal and utilization of diseased elm wood would be an important way to minimize the impact of this disease on the urban elms and may reduce disease incidence in the lowland forests. The timing of such removal depends on the vector involved. Where the European bark beetle is the primary disease carrier, infected trees should be removed and utilized by May 1 of the year following infection. This will kill beetles which overwinter in the wood. Where the native bark beetle is a primary vector, infected trees should be removed in the summer to kill the beetles already in the wood and to prevent adult beetles from finding wood to lay their eggs in. If removal is delayed, most of the beetles will emerge and fly to healthy elms to overwinter.

Proper utilization of diseased elm has been described (Dark 1978, Neely 1975). Proper utilization will ensure the infested wood will not be a source of disease for areas where the wood is transported to.

Harvesting Implications
An increase in the harvesting of elm will likely decrease the incidence of Dutch elm disease especially if the diseased elm wood is utilized properly.

B.4.2
Trunk Rot of Red Maple - *Inonotus glomeratus*

Red maple is considered to be very susceptible to defect. Decay and discoloration advance faster in red maple that in sugar maple (Shigo 1969a). The principal decay fungus in red maple is *Inonotus glomeratus*. This fungus

enters the tree through wounds such as dead branch stubs and logging wounds (Shigo 1969b).

Harvesting Implications
Harvesting red maple could increase the incidence of trunk rot in trees left (residuals) after a logging. This could occur if the residual red maple were wounded during logging.

B.5
Pine

B.5.1
Jack Pine Stem Rusts - *Cronartium quercuum, C. comptonia, C. comandrae,* and *Endocronartium harknessii,*

All of these diseases are caused by fungi that cause galls or swellings on jack pine seedlings or branches and galls or cankers on the main stem. Damage includes growth reduction, provision of an entry court for decay fungi and insects, and death by girdling or wind breakage. These diseases can be managed by removing infected trees during TSI or thinnings. In heavily infected stands, conversion to another tree species should be considered (Robbins and others 1981).

Harvesting Implications
An increase in the harvest of jack pine should reduce the incidence of these rusts as long as the site is regenerated with noninfected nursery stock, natural regeneration, or a species other than jack pine.

B.5.2
Armillaria Root Rot of Red Pine - *Armillaria spp.*

These are all diseases of red pine that should be considered when choosing the best site for planting red pine. Armillaria root rot will use hardwood stumps (such as oak and aspen) as a food base while it extends its rhizomorphs (bundles of mycelium) through the soil, infecting live red pine roots. Therefore, hardwood sites that have been harvested and are being planted to red pine can support a high population of Armillaria and pose a threat to red pine. Losses have been recorded up to 37 percent over a 10 year period (Pronose and Patton 1977). Losses are usually less than 10 percent however, and are heaviest 5 to 9 years after hardwoods have been cut.

B.5.3
Diplodia Shoot Blight and Canker - *Sphaeropsis sapinea*

Diplodia shoot blight and canker infects the growing shoots of red pine, grows down into the branch and main stem and may eventually cause a stem canker. This fungus may also directly invade the main stem through wounds

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and cause cankers (Nicholls and Ostry 1990). Infected shoots are killed; whole branches and tree tops may die. Diplodia has been observed to be more severe on dry sites (Palmer 1991). Very droughty sites or sites with a history of Diplodia should not be planted to red pine.

B.5.4
Scleroderris Canker - *Ascocalyx abietina*

Scleroderris canker (the Lake States strain) is present in northern portions of Michigan, Wisconsin, Minnesota, Vermont, and New York. This disease has been observed to be most serious in forest areas above latitude 45 degrees north or at high elevations where summers are cool and the frost-free period is less than 90 days (Skilling 1968). The infection process begins in the buds and needles of red pine; the fungus then moves down the branch and into the main stem where a canker commonly forms. A high percentage of trees may be killed in stands heavily infected during the first 5 years after planting. The incidence of this disease is often highest in areas known as "frost pockets", or bowl-shaped depressions in the landscape (O'Brien 1972, Skilling and others 1986). To minimize the incidence of this disease, nursery stock must be free from disease and frost pockets should not be planted with red pine in the susceptible areas of the state.

B.5.5
Red Pine Shoot Blight - *Sirococcus conigenus*

Red pine shoot blight caused by *Sirococcus conigenus*, causes shoot mortality of red pine and is most serious in red pine growing in uneven-aged stands. Disease incidence has been reported as being highest on the understory in these uneven-aged stands (Ostry and others 1990). Growth loss, deformity, and death may occur to infected trees (Nicholls and others 1981). Management includes not planting red pine adjacent to infected trees because spores are disseminated from infected trees by rainsplash. Provide a buffer zone between infected overstory and seedlings that is at least twice the height of the infected overstory.

B.5.6
White Pine Blister Rust - *Cronartium ribicola*

White pine blister rust is caused by a rust fungus that requires 2 hosts to complete its life cycle, white pine and either gooseberry or currant bushes. In fall, the rust fungus releases spores from the underside of the gooseberry or currant leaves that infect the pine needles. For successful infection to occur, the pine needles must be wet and the air temperature must be between approximately 50 and 60 degrees F and the relative humidity between 97 to 100 percent for at least 48 hours (Miller and others 1959, Anderson 1973). Injury to infected trees includes dead branches, stem cankers, and mortality. These strict requirements for infection have been studied by Van Arsdel (1961) who has divided the Lake States into blister

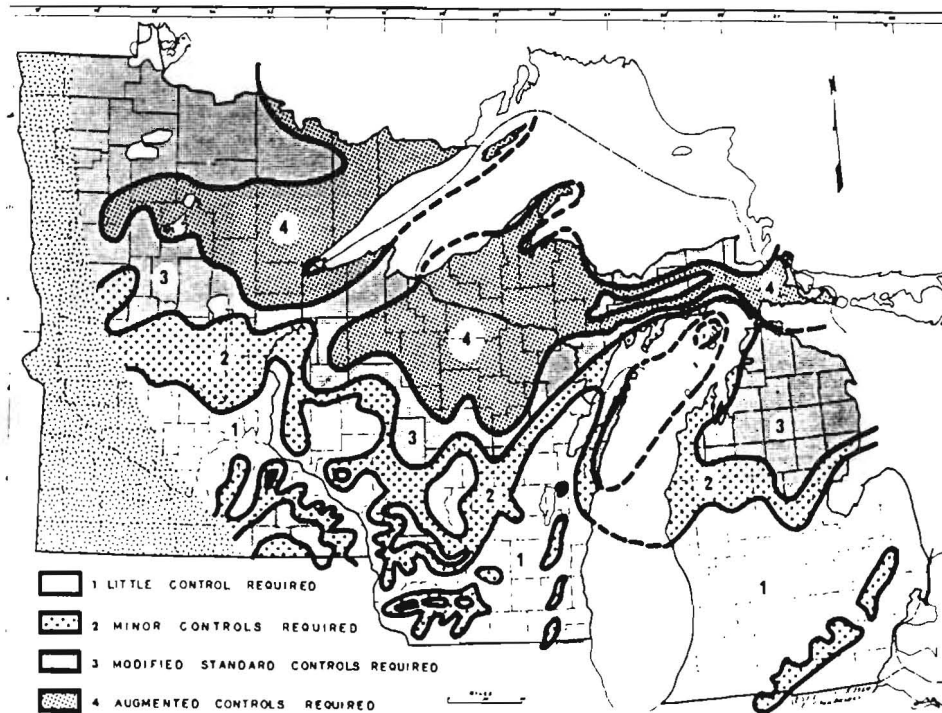rust hazard zones based on the likelihood of successful infection and development of this disease (figure 1).

Figure 1. Climatic hazard zones for white pine blister rust infection potential, ranging from Zone 1 with low potential to Zone 4 with a very high potential.

Van Arsdel found that this disease is most abundant in areas with low daily maximum temperatures or with long daily cool periods. This occurs under small openings in the forest canopy, at higher latitudes and higher elevations.

Harvesting Implications
Some guidelines for managing white pine blister rust are summarized from Van Arsdel (1961):

In hazard zone 1, no preventive measures are necessary to manage this disease, and no effect of increasing the harvest of white pine on disease incidence is expected.

In hazard zone 2, white pine plantings should be limited to dry or sandy hilltops, steep slopes or open fields. Do not plant white pine in small forest openings (with diameters less than the height of the surrounding trees), at the bases of slopes, V-shaped valleys or in other topographical depressions. If these guidelines are not followed, an increase in blister rust may be expected.

In hazard zone 3, use precautions listed for hazard zone 2, and plant white pine only under solid canopies; canopy trees should be oak, aspen, paper birch or jack pine. In release cuttings, make no openings larger than a single aspen or paper birch crown, and make these only in trees 6 inches in diameter or larger. An increase in the harvest of white pine in hazard zone 3 could increase blister rust incidence unless these guidelines are followed.

In hazard zone 4, use precautions listed for hazard zone 3, and consider alternative tree species. An increase in the harvest of white pine in hazard zone 4 could increase blister rust incidence unless these guidelines are followed.

B.6
Spruce - Fir

B.6.1
Trunk, Root and Butt Rots of Balsam Fir and White Spruce

There are several fungi that cause root, butt, and trunk decay of balsam fir and white spruce (Davidson 1957, Prielipp 1957, Whitney (1961, 1988). Some of the more common are Armillaria root and butt rot of balsam fir, *Haematostereum sanguinolentum* trunk rot of balsam fir, and *Inonotus tomentosus* root rot on white spruce. As balsam fir and spruce mature, these organisms spread within and between trees and cause decay of living trees and mortality. Several authors have shown a relationship between age of balsam fir and incidence of root and butt rot. Whitney (1988) found that root rot of balsam fir became significant at 51-60 years of age (about 20 percent of the crop trees dead or windfallen). His study was conducted in Ontario where he found after 68 years, 15 and 35 percent of the gross merchantable volume of white spruce and balsam fir respectively, were lost to root, butt and trunk rot. Prielipp (1957) recommends rotation ages for balsam fir in upper Michigan to be 65-70 years on swamp sites, 55-60 years on transitional sites and 45-50 years on upland sites. Kaufert (1935) observed that balsam fir cull in Minnesota increased rapidly after 70 years.

Inonotus tomemtosus occurs in spruce on a variety of sites, but the disease is most prevalent where soils are very acidic, (pH4-5), and low in nutrients and moisture-holding capacity. On these sites, if root rot is present, losses can be minimized by clearcutting and converting to another less susceptible species such as pine, balsam fir, or hardwoods. (Whitney 1977).

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Harvesting Implications

An increase in the harvesting of the spruce-fir type might lead to a decrease in the incidence of root, butt and trunk rots if the cutting reduces the average stand age to below 50 years.

Root rot caused by *I. tomentosus* may also be reduced by increasing harvesting of white spruce if stands with this root rot are chosen for cutting, and the stand is clearcut. In heavily infected stands, a clearcut followed by conversion to a less susceptible species will reduce root rot.

B.7
Upland Hardwoods

B.7.1
Sapstreak of Sugar Maple - *Ceratocystis coerulescens*

Sapstreak of sugar maple is caused by the fungus *Ceratocystis coerulescens*. This fungus causes a green stain in the root collar region of sugar maples and is positively associated with wounds (Houston 1985). The stain causes a decrease in wood value and infected trees may not be salvageable for lumber (Ohman and Spike 1966). Sapstreak may also cause twig and branch dieback, chlorosis, thin or dwarfed foliage, and eventually lead to tree mortality (Hepting 1944). This disease has been reported from Wisconsin and the Upper Peninsula of Michigan (Kessler 1972, Kessler and Anderson 1960). Even though sapstreak has not been reported in the literature as a forest pest in Minnesota, its presence in adjoining states and its association with logging wounds rank it as an important disease to consider when calculating the effects of harvesting on sugar maple.

The disease is spread by insect disseminated spores that infect trees through root and basal trunk wounds. Infected trees are commonly located along skid trails where they are likely to be wounded when logs are skidded. In Menominee County, northeastern Wisconsin, 431 trees along skid trails were examined for the presence of sapstreak (Mielke and Charette 1989). Of the wounded trees, 4.8 percent were infected with sapstreak which equals 1 tree per 21.2 chains of skid trail.

Harvesting Implications

If the area of upland hardwoods harvested is increased, and harvesting methods such as shelterwood or selection are used, more residual sugar maple may be wounded and possibly infected with sapstreak. Also, an increase in the number of entries into a stand will increase the chances of wounding and infecting residuals. Preventing injuries to the roots is the most effective management and prompt removal of infected trees during timber stand improvement (TSI) operations is also advisable.

B.7.2
Cankers of sugar maple and yellow birch - *Nectria galligena* **on sugar maple and yellow birch and** *Eutypella parasitica* **on sugar maple**

Nectria canker causes a localized area of dead tissue on the main stem of sugar maple and yellow birch. This fungus infects trees through bark injuries and usually infects sugar maple when they are 2 to 20 years old. Yellow birch may be infected throughout its life time. Nectria canker is often on the lower 10-foot section of the tree where it can cause serious losses in timber quality. Certain geographical areas near large lakes such as Lake Superior and Lake Michigan, are especially high hazard zones for this disease (Anderson and Moser 1979). Eutypella canker is also a wound pathogen and requires exposed xylem as an infection court. This disease most frequently kills trees less than 7.5 cm in diameter. On larger maples, cankers reduce wood quality and increase the risk of wind breakage (Robbins 1979).

Management recommendations for minimizing the impact of Nectria canker have been outlined by Anderson and Moser (1979) and are as follows:

In mature stands, if more than 20 percent of the selected species to be favored in regeneration are infected, regenerate to less susceptible species such as red oak, hickory, ash, or maple. In immature stands, if less than 20 percent of the crop trees are infected, remove infected stems during timber stand improvement (TSI). If 20 to 50 percent of the crop trees are infected, remove infected stems during TSI and plan a short rotation. If more than 50 percent of the crop trees are infected, regenerate to less susceptible species.

Management for minimizing the impact of Eutypella canker include the following:

Remove cankered trees during TSI and minimize stem wounds on trees through proper layout of logging roads and minimizing the number of entries into a stand.

Harvesting Implications
Shelterwood and selection cuts: If wounding of residuals is minimized, number of entries into a stand are kept at the current level, and cankered trees are removed during TSI, canker incidence would probably remain at about the same level or decrease. If the number of entries into a stand is increased, there is a risk of increasing the number of wounds and cankers on these species.

Clearcuts: Clearcutting these species should reduce the incidence of disease by eliminating infected trees. The incidence of this disease is usually low; clearcutting to decrease disease incidence is unnecessary.

B.7.3
Decay of Sugar Maple - *Oxyporus populinus* **and Others**

There are many fungi that decay sugar maple; *O. populinus* is one of the most common decays of sugar maple in the Lake States area. Shigo (1965a, 1965b, 1966) has shown a relationship in northern hardwoods between tree wounds and decay and discoloration. Decay caused by *O. populinus* seldom extends more than 1 meter above or below the fruiting bodies of the fungus. Decay associated with *Inonotus glomeratus*, frequently found on sugar maple, can be much more extensive.

A relationship between stem wound size and decay has been observed (Hesterberg 1957, Ohman 1970). Hesterberg observed a 50-50 chance of decay developing within 10 years from a stem wound covering 150 or more square inches and a wound this size could lead to a 10 percent loss of volume by 20 years. Ohman found that exposure of 50 or more square inches of sapwood usually lead to decay and discoloration within 10 years. Wounds which occur to residual trees during a partial harvest or TSI can be critically important. In New York State, a study looking at logging damage in partially cut hardwood stands found that skidding damaged 22 trees per acre and caused major wounds on 4 square feet of basal area per acre. Felling affected 35 trees per acre (about 16 percent of the total residual growing stock) and resulted in major injury to 8 square feet of basal area (Nyland and Gabriel 1971). Wounds also occur when branches die. Rapid death and shedding of branches, followed by rapid branch stub closure minimizes development of discolored and decayed wood.

Minimizing wounding during logging and maintaining a level of stocking to promote natural branch shedding, are keys to managing sugar maple.

Harvesting Implications
Shelterwood and selection cuts: Sugar maple is often managed with uneven-aged management that requires repeated stand entries which can result in damage to the residual trees. If repeated entries are planned, the manager should plan to minimize logging injury through careful road layout, and limiting logging to periods when the ground is frozen. Removing trees with large wounds during TSI or other partial cuttings (if the stand is not to be revisited within 10-15 years) will also reduce the incidence of decay. Long intervals (>15 years) between cuts may allow decay from logging damage to develop into an economic factor.

Clearcuts: Clearcutting would avoid the problem of wounding residual sugar maple and would probably reduce the incidence of decay. The benefits of clearcutting northern hardwoods to reduce decay have to be weighed with the benefits of growing and harvesting northern hardwoods in an uneven-aged system with selection or shelterwood cuts.

B.7.4
Oak Wilt - *Ceratocystis fagacearum*

Oak wilt is widespread throughout central and southeastern Minnesota. Red and black oaks are very susceptible to this killing disease. White oak is somewhat resistant and may not die when infected. Once a tree becomes infected, the fungus produces spore masses on mats of mycelium under the bark. These spore masses have a fermenting odor that attracts insects, especially sap-feeding beetles called Nitidulids or picnic beetles. These insects may transmit the disease from diseased trees to healthy trees by feeding on the fungal mats then feeding on the sap flow from fresh wounds on healthy trees. The disease may also be transmitted through root grafts or connected roots of healthy and diseased trees.

Overland spread of oak wilt can be minimized by proper timing of oak harvesting in oak wilt infested areas. Wounds created on healthy residuals during a selection or shelterwood cutting can serve as infection courts for this disease. Wounds created in May and June in Minnesota (French 1991) are the most likely wounds to be infected and partial cuttings should not be conducted in areas with active oak wilt (figure 2) during these months. Clearcutting oak should not present a hazard unless healthy oaks are wounded around the clearcut or along skid trails that give access to the clearcut.

There is also a hazard associated with moving red or black oak trees from the forest if fungal mats are present; the disease may be moved with the logs. Trees wilting in June, July-August, or September, will form fungal mats in September of the same year, October of the same year or May in the following year, and June or later in the following year respectively. If recently infected trees are girdled while still standing, the cambium will dry out and fungal mat formation can be prevented. If the mats have formed, the bark should be removed or the wood chipped. If the bark is not removed or the wood chipped, the wood should be wrapped in plastic prior to May 1 and kept covered until July 1 (French 1980).
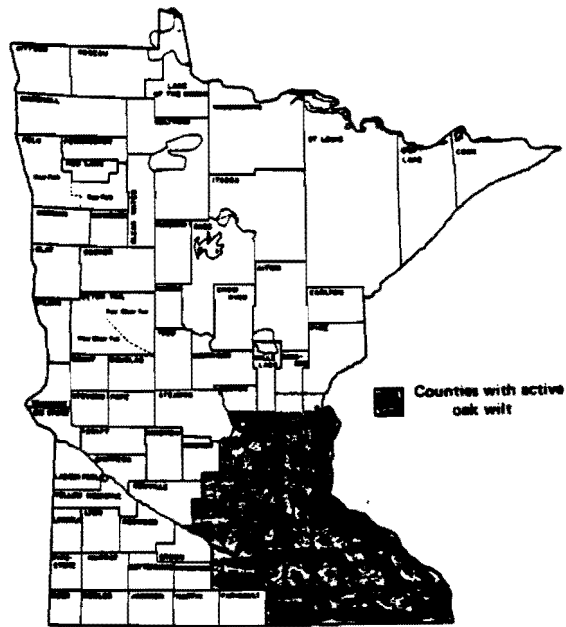
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Figure 2. County distribution of oak wilt (from the Interagency Oak Wilt Program Progress Report, 1988-1989, Minnesota Departments of Agriculture and Natural Resources and University of Minnesota).

Harvesting Implications

Shelterwood and selection cuts: When conducting a selection cut or shelterwood in areas where oak wilt is present, logging should not occur in May and June. If an increase in harvesting of oak occurred in these months in oak wilt areas, disease incidence would probably increase in 1 to 2 years.

Clearcuts: An increase in the clearcuts of oak would probably reduce the incidence of oak wilt unless oaks surrounding the cuts or along access trails were wounded during May and June.

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B.7.5
Armillaria Root Rot on Oak Following Drought - *Armillaria* **spp.**

It has been well documented that Armillaria root rot is a secondary pathogen, attacking oaks weakened by biotic or abiotic stresses (Wargo and Shaw 1985, Houston 1981). It is also well documented that from 1987 through 1990, Minnesota suffered from severe and widespread drought (Hayes and Albers 1991). The drought stress together with defoliation by the forest tent caterpillar and infestation by the two-lined chestnut borer, caused mortality of oak from 10-20 percent in 1988 in central Minnesota to 70 percent in 1989 and 80 percent in some of the northern regions in 1990.

Harvesting Implications
Any harvesting practice that has a goal of regenerating a healthy oak forest from a dying oak forest or converting the site with high mortality into some other timber type appropriate for the site, will decrease the amount of Armillaria root rot on oak.