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Silvicultural Guidelines for Forest Stands Threatened by the Gypsy Moth

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Abstract

Silvicultural treatments that may minimize gypsy moth impacts on host hardwood stands are recommended based on ecological and silvicultural information. Decision charts are presented that match the proper prescription to existing stand and insect population conditions. Preoutbreak prescriptions focus on reducing stand susceptibility and vulnerability by increasing stand vigor, removing trees most likely to die, reducing gypsy moth habitat, reducing preferred gypsy moth food sources, improving predator and parasite habitats, and regenerating stands that are close to maturity or understocked. Regeneration cuttings before defoliation preserve seed production, established advanced regeneration, and stump sprouting potential. Outbreak prescriptions prioritize stands for possible insect population control actions and regenerate stands that are close to maturity or understocked. Postoutbreak prescriptions center on efficient salvage of dead trees and the regeneration of stands that are either understocked due to excessive mortality or are close to maturity. Information on utilization of dead trees is provided. While these guidelines have not been extensively tested, they represent the current knowledge of the impacts of gypsy moth defoliation on forest stands.

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Cover photo: This West Virginia stand received a presalvage thinning before gypsy moth defoliation. The susceptible oaks have been defoliated completely, while the immune yellow-poplar tree has not been touched. (Photo by David L. Feicht, USDA Forest Service.)

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INTRODUCTION

As the gypsy moth has moved south and west from New England into large areas of commercial forests in the Appalachian mountains, it has impacted many sectors of the forestry community (McManus and others 1989). Gypsy moth defoliation has affected recreation, hunting, wildlife habitat, and water yield and quality. Resulting tree mortality has adversely affected local timber supplies and prices within heavily infested areas preempting forest management on thousands of acres (Donley and Feicht 1985; Quimby 1985). This report synthesizes current knowledge and updates silvicultural prescriptions for coping with the gypsy moth that were published previously (Gottschalk 1982, 1987). It is primarily a guidebook for foresters whose goal is timber production. It also allows for inclusion of other goals such as recreation, wildlife habitat, and esthetics in decisionmaking and silvicultural prescriptions. These recommendations are not prescribed to directly control the gypsy moth in forest stands or across the infested area, but **are designed to minimize gypsy moth impacts** before, during, and following the occurrence of defoliation.

The guidelines presented here can be used throughout the oak-hickory, oak-pine, oak-gum-cypress, and northern hardwoods forest types and their variants in the Eastern United States. These types are potential gypsy moth targets; however, they differ in susceptibility and vulnerability to gypsy moth. Specific modifications can be made by using these guidelines in conjunction with local and regional guides in particular those recommended for upland central hardwoods (Roach and Gingrich 1968), oaks in the North-central states (Sander 1977), oaks in New England (Hibbs and Bentley 1983), and hardwood stands of the Alleghenies (Marquis and others 1992).

These prescriptions are based on treatments that are appropriate to particular combinations of stand and insect conditions. Decision charts are used to match the stand and insect conditions to these treatments. Most of the prescriptions have not been extensively tested. They are guides subject to modification using professional judgment to make them fit specific stands or management objectives. Any feedback or comments on problems that are encountered in the use of, or suggestions for improvement in, the guidelines are welcome and should be directed to the author.

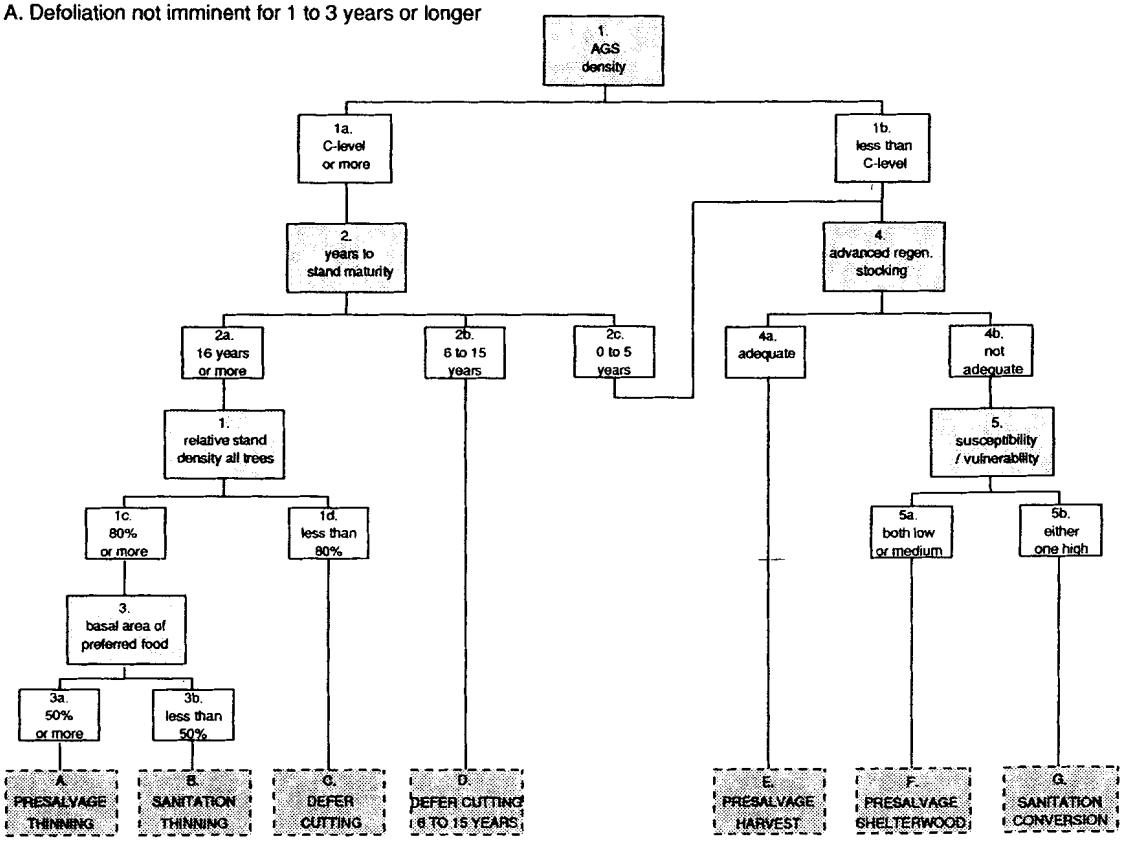
SILVICULTURAL GUIDELINES

This section provides guidelines and instructions for determining silvicultural prescriptions that can be applied to reduce losses caused by gypsy moth defoliation in forest stands threatened by the pest. This process requires stand examination to determine the present overstory, understory, and site conditions; stand analysis to assess the stand's characteristics and potential for future growth and regeneration; gypsy moth population monitoring to determine the potential for defoliation; and stand prescription to determine the appropriate silvicultural techniques to be used to meet management objectives based on the stand and insect conditions, and to provide information on application of these techniques.

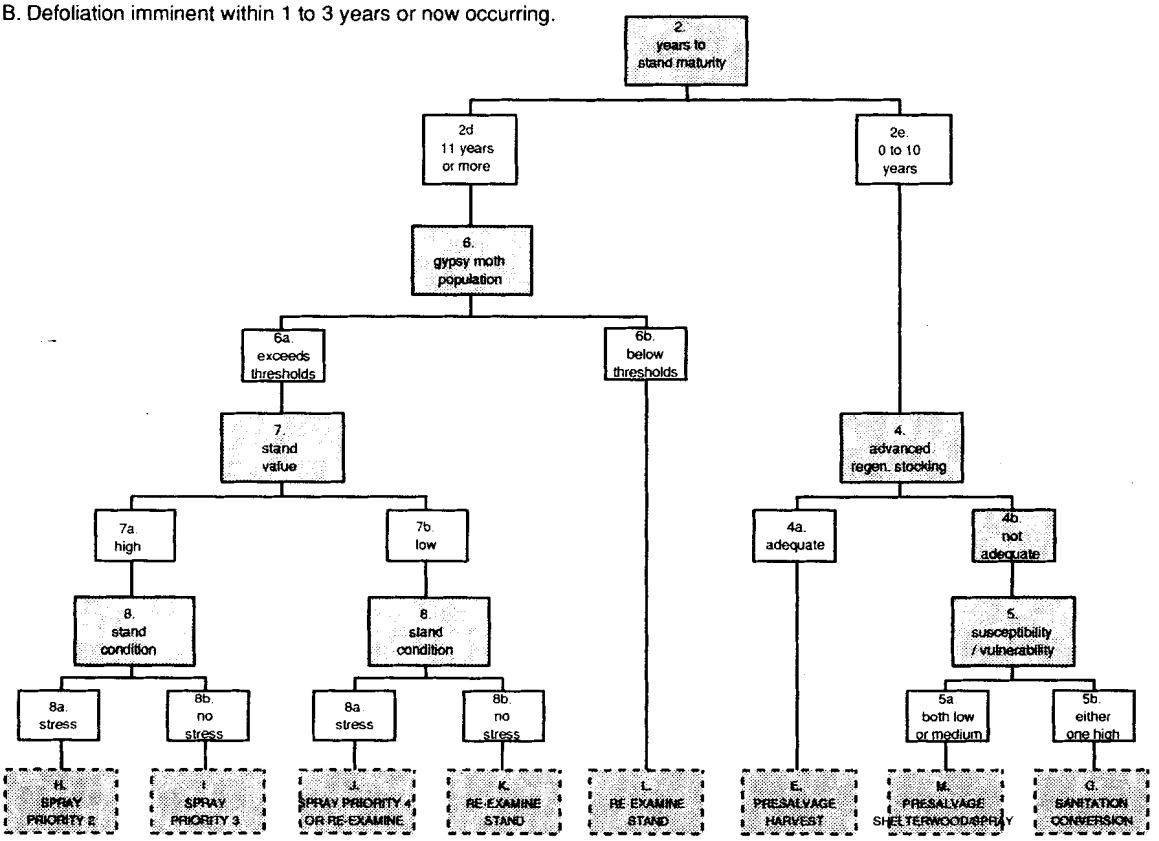
Determining Appropriate Treatment

The guidelines for minimizing gypsy moth impacts are shown in decision charts (Fig. 1A-C) These decisionmaking aids have been divided into three sets based on the imminence of defoliation. Forest managers should use the decision chart that corresponds to the temporal position of their forest stand relative to defoliation. Once the imminence of defoliation has been determined, it is necessary to complete a stand examination or inventory of both overstory and regeneration conditions and to monitor gypsy moth populations. This information will provide stand characteristics that are needed to use decision points in the flow charts.

A. Defoliation not imminent for 1 to 3 years or longer



B. Defoliation imminent within 1 to 3 years or now occurring.



C. Defoliation has occurred, wait 1 to 3 years for mortality to occur.

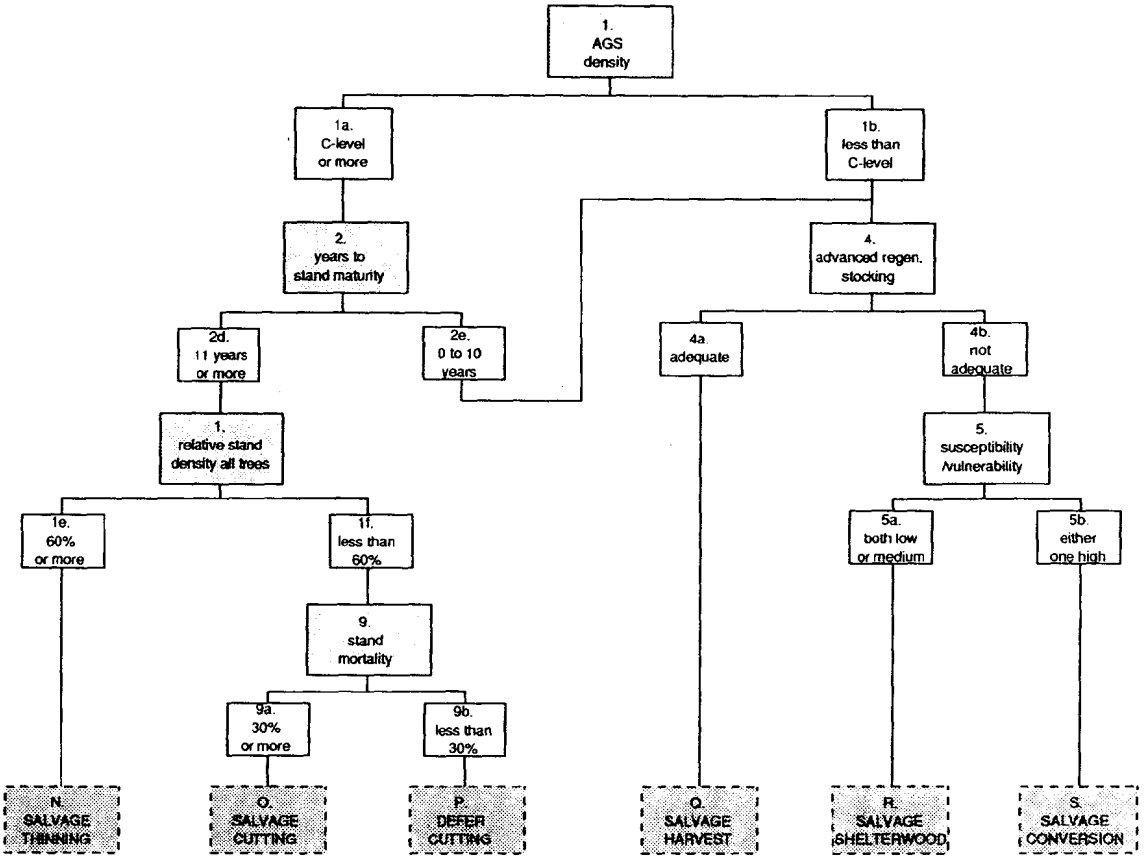


Figure 1A,B,C.—Decision charts for silvicultural treatment prescriptions based on the imminence of defoliation, stand, and insect conditions.

Imminence of Defoliation

It is important to determine the stand's potential for defoliation to know which treatments are possible and appropriate. Three categories of defoliation imminence are used: 1) defoliation not imminent within 1 to 3 years, 2) defoliation imminent within 1 to 3 years or now occurring, and 3) defoliation has occurred, wait 1 to 3 years for mortality to occur. The first category is usually appropriate for stands located outside the generally infested area, while the latter two categories usually apply to stands located within the infested area. The major change in guidelines presented here is a reduction in the imminence of defoliation lead time from 3 to 5 years down to 1 to 3 years based on recent research results.[1]

Imminence of defoliation can be determined from information on the location and spread of gypsy moth populations into new areas and by population monitoring in generally infested areas. These data are collected by the USDA Animal and Plant Health Inspection Service (APHIS) in areas that are not currently infested, and in currently infested areas by the forest pest management staffs of state agencies (agriculture, natural resources, or forestry), or by the Forest Pest Management staff (USDA) Forest Service) on federally owned land. Pest management specialists can help you estimate the imminence of defoliation by providing information on the location and size of the area currently infested with local gypsy moth population levels and expected trends, and the time when the infestation would be expected to affect lands you manage.

[1]Gottschalk, Kurt W. In preparation. Effects of previous stand management on mortality following gypsy moth defoliation.

Defoliation Not Imminent Within 1 to 3 Years. In uninfested areas, imminence of defoliation is best determined by the pest management specialist using the data described above. Initial infestations and low-level populations are detected with traps baited with gypsy moth sex attractants. These pheromone traps attract male moths and can be placed in the forest on a grid pattern that will detect low-level populations earlier than any other method (Schwalbe 1981). The above-named agencies may already be using these traps in the area. Widespread detection (high frequency of positive catches) of male moths will indicate that the 1- to 3-year limit is being approached.

In the generally infested area, ongoing monitoring of population levels may allow the pest management specialist to predict the next outbreak. However, gypsy moth populations can build so rapidly (1 to 2 years) from low levels that are almost undetectable to outbreak levels that this may be a futile task. Once an area has been infested, fewer stands will be in this category due to fluctuations of gypsy moth populations (Wallner 1982) and the necessity of waiting 1 to 3 years following an outbreak before salvaging.

In stands where defoliation is not likely to occur within 1 to 3 years, the primary objectives of these guidelines are to reduce stand susceptibility and vulnerability and to regenerate understocked stands and stands near maturity before they are defoliated (Fig. 1A). It is believed that stand susceptibility may be reduced by decreasing preferred food species, removing refuges for larvae, promoting predator and parasite habitat, and increasing forest diversity. Stand vulnerability may be reduced by eliminating high-hazard trees, improving stand and tree vigor, and reducing secondary organisms.

Defoliation Imminent Within 1 to 3 Years or Now Occurring. Once widespread detection (high frequency of positive catches) of male moths has occurred in previously uninfested areas, the placement of burlap bands around a few preferred host trees will allow the detection of gypsy moth larvae. It is possible to have high male moth populations without detecting any other gypsy moth life stages in the area. As soon as larvae (or caterpillars) have been detected in the area, defoliation may occur within 1 to 3 years, if not sooner. Once larvae have been detected in the area, egg-mass sampling can be used in individual stands as an indicator of population levels. In a generally infested area, burlap banding of selected trees can be used to assess populations that are starting to build. Egg-mass sampling, again should be used to determine the need for action. These sampling activities can be done by the forest pest specialist if their time and resources permit or by the forester, who then uses the forest pest specialist as a source of information and interpretation.

In stands where defoliation is imminent or now occurring, the primary objective is to protect stands that are at high risk and have high value, and to regenerate stands that are close to maturity before they are defoliated (Fig. 1B). Stand value and condition are used to prioritize stands for aerial spraying once a population control threshold has been exceeded; it is not economically feasible to treat all stands. Four levels of spray priorities have been established.

Defoliation Has Occurred, Wait 1 to 3 Years for Mortality to Occur. Aerial defoliation surveys are conducted annually by most of the state and federal forest pest management groups. Their defoliation maps along with field visits to stands during the defoliation period can be used to determine if an area has been moderately to heavily defoliated during a gypsy moth outbreak.

In stands where defoliation has occurred, the primary objectives are to salvage mortality, regenerate stands that are understocked due to excessive mortality, and regenerate stands that are near maturity (Fig. 1C). Mortality will occur over a period of several years, but the majority will occur within a single year, generally 2 to 3 years after defoliation. The timing of mortality should be carefully monitored because the manager should allow the bulk of the mortality to occur before deciding on the appropriate treatment for the stand. Dead timber loses quality and value rapidly (Donley and Feicht 1985). Salvage should occur promptly after the majority of the mortality has occurred. Some mortality probably will occur after 3 years, but it should be minor and not seriously affect the prescriptions.

Decision Charts

Use of the charts is facilitated by identification codes that cross-reference each box on the charts to the appropriate section of explanatory text. Each stand characteristic is assigned a number, while its criterion values are assigned the same number followed by a lower case letter. Each prescription is assigned an upper case letter. To use the chart, start at the characteristic in the top box and follow the line to the box that contains the criterion that matches the stand's value for that characteristic. From that box, follow the line down to the next characteristic. Again, find the box below it that matches the stand's value for the characteristic. Continue down the chart, matching criteria on the chart to values for the stand characteristics until arriving at a prescription in the dashed box at the bottom of the chart. The prescription is recommended for the conditions present in the stand in question. Specific instructions for that prescription and for calculating stand characteristic values are in following sections.

Stand Examination and Analysis

The choice of stand examination techniques is not critical so long as information about overstory and understory conditions is obtained in a manner that provides estimates with a reasonable degree of accuracy. Marquis and others (1992) provide a good discussion and description of how to conduct a stand examination. Standard information that needs to be collected is: number, size, and quality of overstory trees by species or species groups; regeneration potential based on advanced regeneration stocking of desirable and commercial species on small plots, occurrence of interfering understory plants, and site limitations; site class or index; deer pressure; and visual goals. Additional information that needs to be obtained in each stand for gypsy moth guidelines includes: number, size, and volume of dead trees by species or species group, stand physiographic location (that is, ridgetop, plateau or bench midslope, upper slope, lower slope, and stream bottom), aspect, relative moisture availability, past stand history particularly disturbances and stresses (drought, fire, defoliation, frost damage, previous cutting), and relative value of stand for meeting both timber and nontimber management objectives.

Summarizing data collected in the stand examination will provide information on stand characteristics that can be used to determine the appropriate prescription for the stand. Calculation of standard per acre values of basal area, number of stems, volume, and value by species or species groups is the first step. Instructions on summarizing additional stand characteristics required to use these guidelines follow.

Relative Stand Density

The relative stand density (1) (Ernst and Knapp 1985) is determined using one of several stocking guides or charts developed for eastern hardwoods (Gingrich 1967; Leak and others 1969; Marquis and others 1992; Roach 1977; Sampson and others 1983; Stout and others 1987). The relative density of the stand is then compared to management stocking levels. Acceptable growing stock (AGS) is defined as trees of acceptable species, form, and quality that could be selected as crop trees. If acceptable growing stock is below the amount needed to continue managing the stand as a unit, it may be best to regenerate the stand. Gingrich (1967) provides a stocked-unstocked decision line (C-level) for upland hardwoods (Fig. 2). Marquis and others (1992) use 35 percent relative stand density as this decision line.

A stocking level of 80 percent defines the upper management zone (sufficient mortality increase, growth decline, and volume present to thin). The lower management zone is 60 percent or B-level stocking (minimum residual level to thin to). Stands between 60 and 80 percent stocked usually do not need to be thinned. In Figure 1C, relative stand density refers to the total density of live trees present in the stand following mortality without regard to quality of growing stock and excluding very poor crowned trees that will not survive.

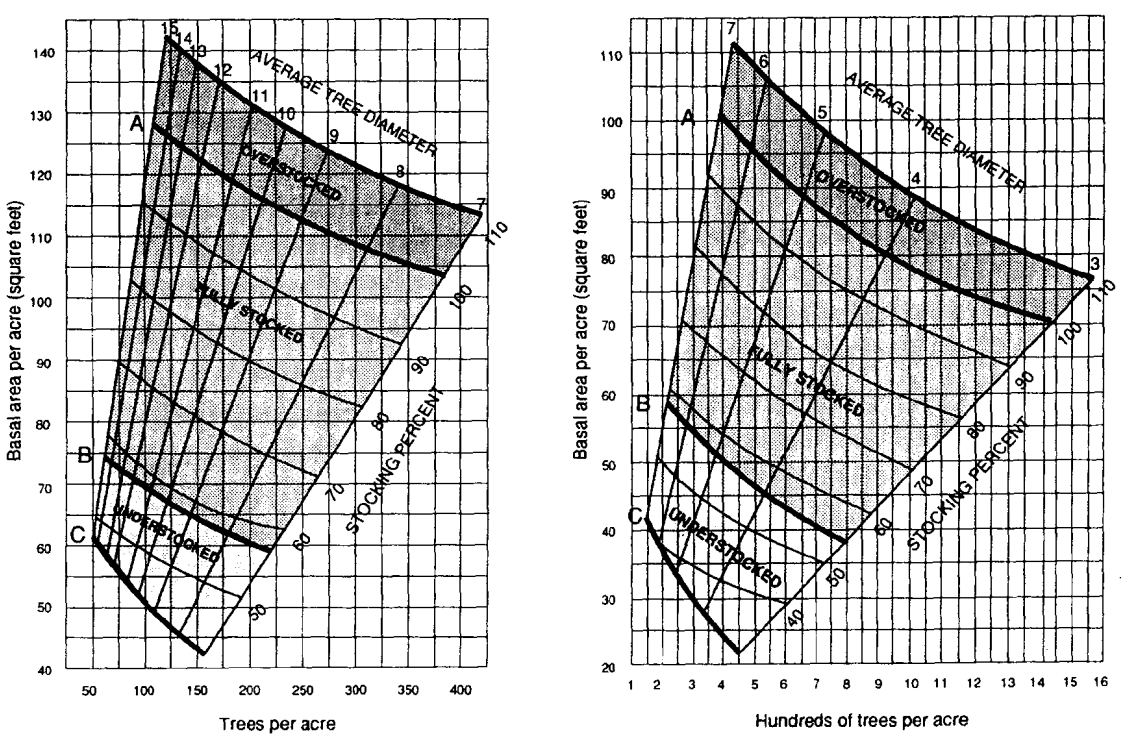


Figure 2.—Relative stand density charts for upland hardwood (oak) stands (redrawn from Roach and Gingrich 1968).

Stand Maturity

Stand maturity (2) can be determined by setting a rotation age to meet management objectives or by calculating financial maturity. Financial maturity can be calculated from the average diameter of merchantable trees, the financial maturity diameter for the rate of return being used (Grisez and Mendel 1972; Mendel and Trimble 1969; Trimble and Mendel 1969), and the projected diameter growth (Marquis and others 1992). Individual tree value growth rates also can be used to help select trees to remove when marking a thinning or improvement cut (Grisez and Mendel 1972; Herrick and Gansner 1985; Mendel and Trimble 1969; Trimble and Mendel 1969; Trimble and others 1974).

Complete investment analysis programs that have been published recently could be used to determine stand maturity as well as other aspects of the economic implications of forest management activities (Utz and Sims 1981, Vasievich 1984).

Basal Area of Preferred Food Species

The basal area (BA) of all preferred (susceptible hosts in Table 1) food species (3) is totaled, divided by total stand basal area, and multiplied by 100. Relative stand density units can be substituted for basal area if desired. This percentage is used to determine if the susceptibility of a stand can be reduced.

Advanced Regeneration Stocking

The presence of advanced regeneration seedlings (4) is critical to the successful regeneration of most eastern hardwoods (Hough 1937; Sander and Clark 1971). Guidelines for evaluating the adequacy of advanced regeneration have been developed for a variety of forest types. The two guidelines that are most appropriate for the forest types affected by gypsy moth are: the Central States oak guide and the Allegheny hardwood guide.

The Central States oak guide uses 4.3-foot radius plots and requires 59 percent of them to contain one 4.5 foot tall or larger oak stem in order to be adequately stocked (Sander and others 1976). If fewer plots are stocked, they can be supplemented with stump sprouts by calculating potential sprouts per acre from stems larger than 2 inches. A recent revision of this method allows seedlings less than 4.5 feet tall to be included based on their probability of success (Sander and others 1984).

Table 1.—Categorization of gypsy moth host preferences (adapted from Mauffette and others 1983; Montgomery 1991; Mosher 1915).

Susceptible:	species readily eaten by gypsy moth larvae during all larval stages.
Overstory:	apple, basswood (American linden), bigtooth and quaking aspen, gray, paper (white), and river birch, larch (tamarack), mountain-ash, most oak species, sweetgum, willow.
Understory:	hawthorn, hazelnut, hophornbeam, hornbeam, serviceberry, witch-hazel
Resistant:	species fed upon when preferred foliage is not available and/or only by some larval stages.
Overstory:	beech, black (sweet) and yellow birch, blackgum (tupelo), boxelder, Ohio and yellow buckeye, butternut and black walnut, sweet and black cherry, chestnut, eastern cottonwood, cucumbertree, American and slippery elm, hackberry, eastern hemlock, most hickory species, Norway, red, and sugar maple, pear, most pine species, sassafras, most spruce species.
Understory:	blueberries, pin cherry, chokecherry, paw paw, persimmon, redbud, sourwood, sweetfern.
Immune:	species that are rarely fed upon.
Overstory:	most ash species, baldcypress, northern catalpa, eastern redcedar, balsam and fraser fir, American holly, horsechestnut, Kentucky coffee-tree, black and honey locust, silver maple, mulberry, sycamore, tuliptree (yellow-poplar)
Understory:	most azalea species, dogwood, elderberry, grape, greenbrier, juniper, mountain and striped maple, most *Rubus* species, sheep and mountain laurel, spicebush, sarsaparilla, most viburnum species

The Allegheny hardwood guide uses 6-foot radius plots and requires 70 percent of them to contain one 4.5 foot tall or larger oak stem per plot (Gottschalk 1983; Marquis and others 1992). In addition, 25 stems per plot smaller than 4.5 feet are considered adequate stocking. This method also allows the inclusion of stump sprouting potential as a supplement to seedlings, but because of heavy deer browsing pressure on the sprouts, it doubles the number of sprouts required and requires a minimum number of plots to contain seedlings. Stems of other desirable species can be evaluated with this system as well (Marquis and Bjorkbom 1982; Marquis and others 1975).

Both of these guidelines require the same number of large advanced oak seedlings per acre to be present (430 per acre). Strict application of these guides will result in stands that are 60 percent or more oak. If management objectives can tolerate a lower percentage of oak (highly recommended for better quality sites), then the number of adequately stocked oak plots can be supplemented with other desirable species to reach an adequate regeneration level for the stand (Gottschalk 1983). The Allegheny guide will work very well in this manner. If advanced regeneration stocking is adequate, then these stands can be harvested. If it is not adequate, then treatments should be applied to obtain adequate stocking or to supplement natural regeneration such as underplanting of seedlings (Gottschalk and Marquis 1982).

Stand Susceptibility

Stand susceptibility to gypsy moth defoliation is defined as the probability of defoliation by the gypsy moth given that the insect is present. Susceptible stands (5) are characterized by: large numbers of favored food species, abundant refuges for larvae on trees and other favorable gypsy moth habitat, and sparse litter protection and other unfavorable habitat for small mammal predators. Quantification of susceptible stands based on basal area of susceptible species and number of refuges has been completed using discriminant functions (Houston and Valentine 1977, 1985; Valentine and Houston 1979, 1981, 1984). Herrick and Gansner (1986) have developed a means of rating stand susceptibility based on species composition, tree size, and average tree crown condition (Fig. 3). A shortened version based only on species composition has been developed (Table 2). Both methods provide a way for managers to predict relative susceptibility of individual forest stands, but Houston and Valentine's technique is most appropriate in New England behind the leading edge of gypsy moth while Herrick and Gansner's technique is best used in front of the leading edge.

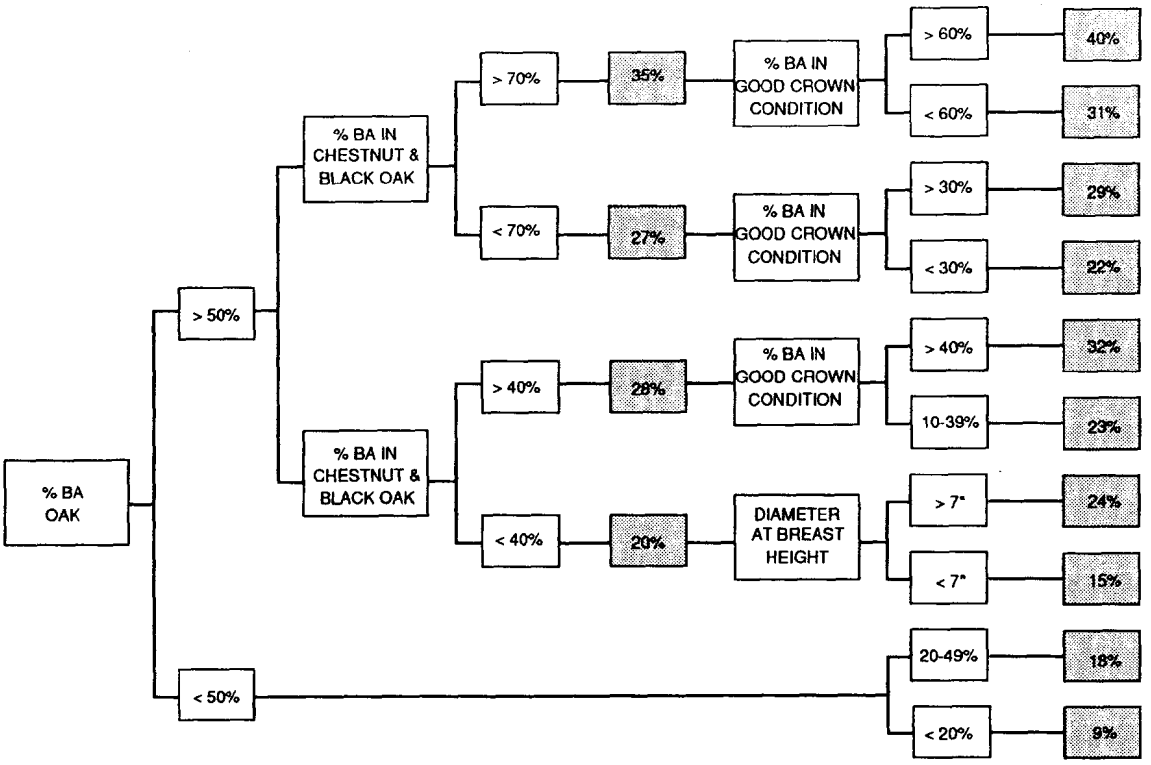


Figure 3.—Guide for estimating gypsy moth 3-year average defoliation potentials (redrawn from Herrick and Gansner 1986).

Table 2.—Stand-level susceptibility to gypsy moth defoliation based only on species composition (adapted from information in Herrick and Gansner (1986)).

Species composition —percent of basal area—	Relative susceptibility
0-20	Low
20-50	Moderate
50-80	High
80-100	Very High

Stand Vulnerability

Stand vulnerability to gypsy moth is defined as the probability of damage occurring in the stand given that defoliation has occurred. The definition of damage can be quite broad: everything from tree mortality to loss of mast production to decreased water quality from increased nitrogen export (for more information, see Gottschalk 1990a; Twery 1991). Although this broad definition of vulnerability is being accepted, most past work and this guide will use tree mortality as the major damage. Vulnerability to mortality (5) is affected by so many interrelated factors and varies so widely that it is very difficult, if not impossible, to predict with precision. However, predictive models indicate what to expect and provide information that will aid managers in making better decisions in the future. More precise models can be developed on a local or regional level than on a larger level since the variability of many factors is reduced. However, these guides may not predict well in areas outside of the region for which they were developed. Vulnerability models for individual trees and stands will be presented.

Individual Trees. Mortality rating guides for individual trees have been developed for the Pocono Mountains of Pennsylvania (Gansner and Herrick 1984b; Herrick 1982), the Ridge and Valley area of Pennsylvania (Herrick and Gansner 1987a), and New England based on the 1911-31 "Melrose data" (Campbell and Valentine 1972; Valentine and Campbell 1975). The Poconos model uses crown condition, species, and aspect to determine vulnerability (Fig. 4). Oak trees with poor crown condition have an 86 percent probability of mortality, while other species with poor crowns have 62 percent probability. Trees with good crowns have only a 2 percent probability of mortality, except for white oaks, which have a 9 percent probability. Trees with fair crowns on N, NE, E, SE, or S aspects had an 11 percent probability of mortality. A similar model for the Ridge and Valley area of Pennsylvania uses crown condition, species group, and crown class to determine vulnerability (Fig. 5). The New England model uses species, crown condition, crown class, defoliation intensity, and defoliation frequency to determine a tree's probability of death. These individual tree models can be used with stand tables to develop stand-level mortality estimates.

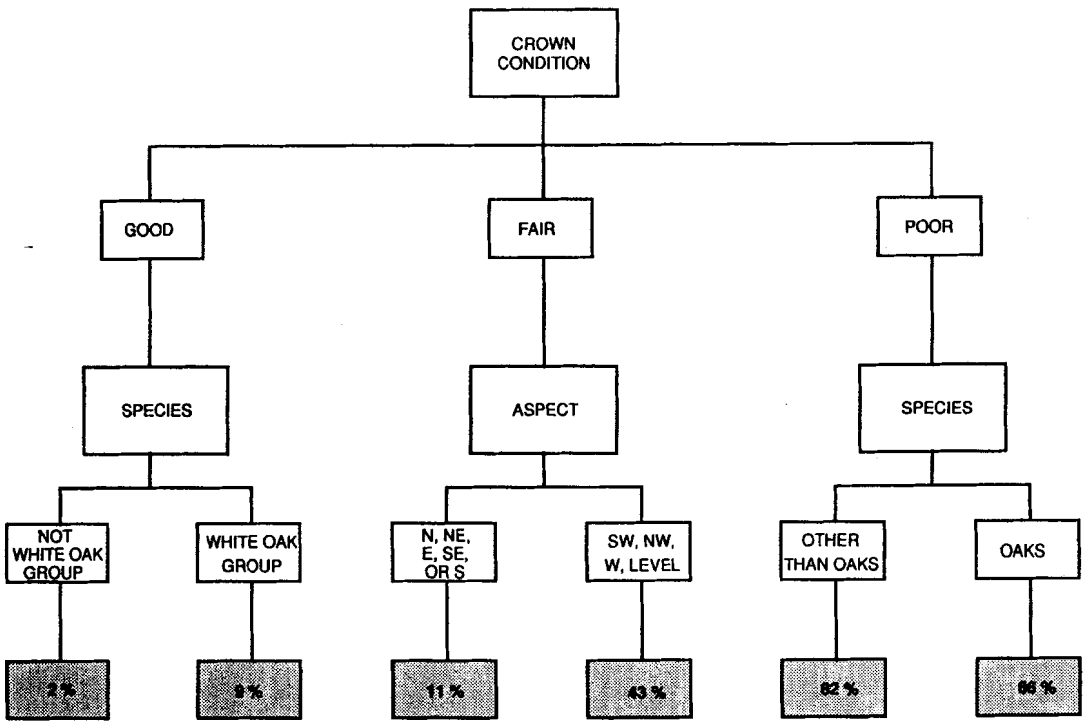


Figure 4.—Guide for estimating probability of individual tree mortality that was developed in the Pocono Mountains of Pennsylvania (adapted from Herrick 1982; Gansner and Herrick 1984a).

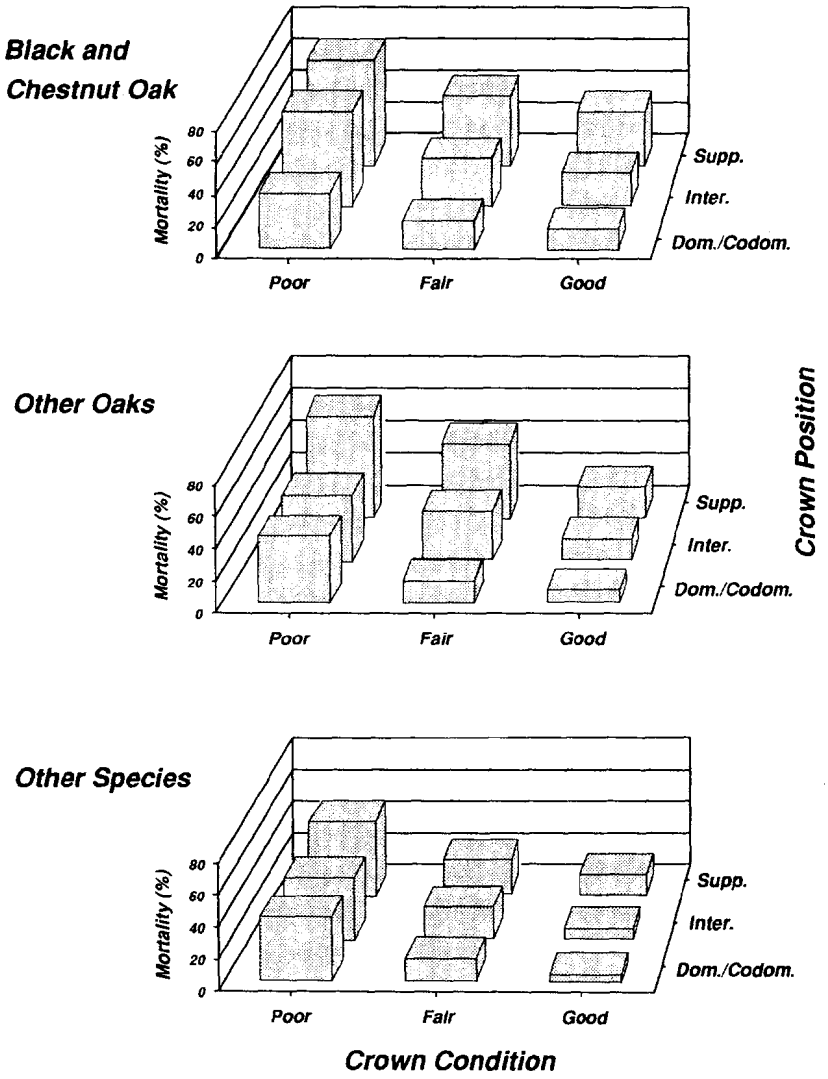


Figure 5.—Guide for estimating probability of individual tree mortality that was developed in the Ridge and Valley of Pennsylvania (adapted from Herrick and Gansner 1987a).

Stands. Stand-level mortality guides have been developed for four areas: (1) New England, (2) New Jersey, (3) northern Pennsylvania (Pocono Mountains), and (4) central Appalachian Ridge and Valley. The New England model can also be used to predict stand responses under a variety of defoliation combinations, species composition, and crown conditions (Valentine and Campbell 1975). Kegg (1974) used a stand susceptibility index, species composition and physical site factors to develop two different stand mortality equations for New Jersey. Two stand hazard rating guides were developed for the Poconos (Gansner 1981). The first one is based on the number (or percentage) of live trees per acre with poor crowns and the number (or percentage) of live trees per acre in the white oak species group (white oak and chestnut oak) (Fig. 6). It produces hazard ratings of low (less than 10 percent mortality), medium (10 to 25 percent mortality), and high (greater than 25 percent mortality) (Gansner 1981; Gansner and Herrick 1984b; Gansner and others 1978). The second guide uses six variables: percentage of trees in poor crown condition, number of trees per acre in white oak species group, number of trees per acre less than 11 inches d.b.h., percentage of trees greater than or equal to 11 inches D.B.H., position on slope, and elevation (Fig. 7). It produces nine groups that have average mortality probabilities ranging from a low of 5 percent to a high of 42 percent (Gansner 1981; Herrick and others 1979). Crow and Hicks (1990) developed a discriminate model for looper complex mortality in Ridge and Valley oak stands of Maryland and West Viriginia. Although it was not based on gypsy moth defoliation, hosts and timing of defoliation are so similar to gypsy moth that it can be used.

Percentage of trees in white oak species group	Percentage of trees with poor crowns						
	0	5	10	15	20	25	30+
0	L	L	M	M	M	M	H
10	L	L	M	M	M	M	H
20	L	L	M	M	M	H	H
30	L	L	M	M	M	H	H
40	L	L	M	M	M	H	H
50	L	L	M	M	M	H	H
60	L	M	M	M	M	H	H
70	L	M	M	M	M	H	H
80	L	M	M	M	H	H	H
90	L	M	M	M	H	H	H
100	M	M	M	M	H	H	H

STAND MORTALITY: L = < 10% M = 10-25% H = > 25%

Figure 6.—Guide for estimating probability of stand mortality that was developed for the Pocono Mountains of Pennsylvania (redrawn from Gansner and Herrick 1984a).

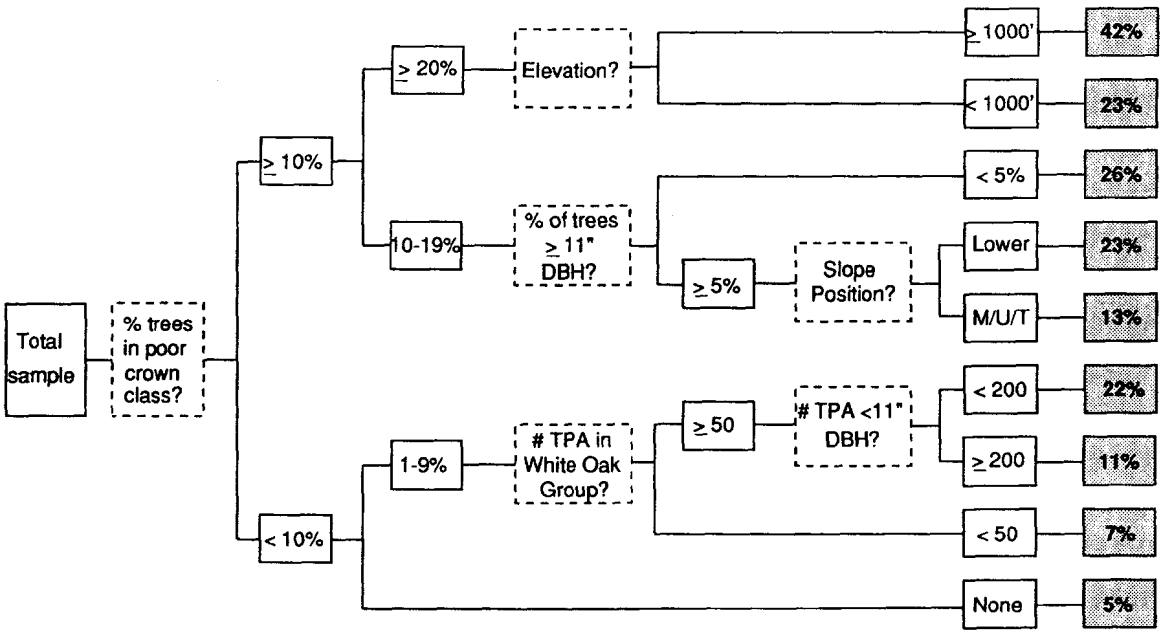


Figure 7.—Guide for estimating probability of stand mortality that was developed for the Pocono Mountains of Pennsylvania (redrawn from Herrick and others 1979).

Gypsy Moth Population

When defoliation is imminent, gypsy moth populations (6) need to be monitored, control thresholds determined, and decisions made on whether to engage in population control treatments. Population control thresholds are developed from treatment effectiveness to meet management objectives of the forest stand and the economic tradeoffs between cost of treatment and potential losses of the stand in relation to its value for meeting management objectives. The term hazard is used for the probability that damage from defoliation will affect the value of the stand for meeting management objectives, while the term risk is used for the timing of potential effects (or hazard) on management objectives. In the context of this guide, sampling gypsy moth populations and the comparison to thresholds for treatment are the final measurements needed to determine risk. If gypsy moth populations are below treatment thresholds then risk is low (even if hazard is high), but as soon as treatment thresholds are exceeded, then risk is either low, moderate, or high depending upon the hazard of the stand.

Sampling Populations. Once gypsy moth populations have been established in an area, egg masses per acre are used to determine potential population levels. Egg masses are evident in infested areas for 7 to 8 months, providing the lead time managers need to make decisions and arrange treatments. Several egg-mass sampling techniques have been used: 5-minute walks, fixed-radius plots, variable-radius plots, and fixed- and variable-radius plots. The "best" technique depends on population size; time, personnel, and money available; and precision of information needed. The "5-minute walk" has been popular (Eggen and Abrahamson 1983), but it has been shown to be biased and does not produce estimates with an adequate level of precision (Fleischer and others 1991; Liebhold and others 1991). The best technique is "fixed-radius plots," usually 1/40 acre, but 1/10, 1/16, and 1/100 acre are used also. It gives accurate population predictions at all population levels but usually takes more time and money to conduct (Liebhold and others 1991; Wilson and Fontaine 1978). Recently, sequential sampling techniques have been developed that provide a more cost-effective and precise means of using fixed-radius plots (Fleischer and others 1991; Kolodny-Hirsch 1986). Additional information and training sessions on egg-mass sampling can be obtained from forest pest management specialists.

Determining Thresholds. The number of egg masses per acre in a stand can be used to predict the ultimate defoliation potential. A method for predicting gypsy moth defoliation percentage from the number of egg masses per acre has been developed (Fig. 8) (Gansner and others 1985; see also Montgomery 1990; Williams and others 1991). The defoliation level expected can be used to determine egg-mass thresholds for population control treatments. Management and landowner objectives determine the type of population control treatment to be used and the foliage protection level that is desirable. Many state programs for aerial spraying are based on preventing tree defoliation as well as the nuisance that is caused by gypsy moth caterpillars. Most suppression projects use thresholds of 250 to 500 egg masses per acre, representing a predicted

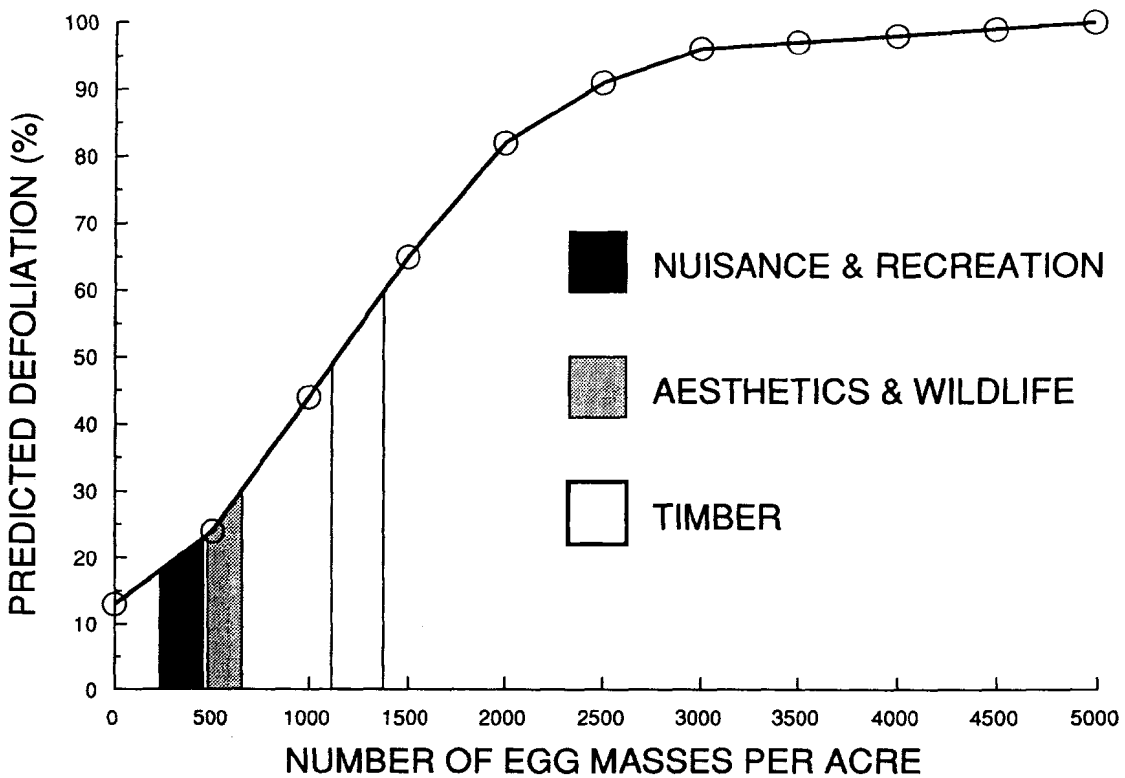


Figure 8.—Guide for estimating stand defoliation level from gypsy moth egg masses per acre (curve redrawn from Gansner and others 1985) and possible managment thresholds.

defoliation potential of 15 to 25 percent (Gansner and others 1985). Foliage protection thresholds to prevent mortality and minimize growth loss in forest stands would be much higher, up to 50 to 60 percent defoliation could be acceptable, or a threshold of 1,200 to 1,400 egg masses per acre (Wargo 1978a). Foliage protection thresholds for aesthetics (30 percent defoliation) might use 700 egg masses per acre, for wildlife mast production (40 to 45 percent defoliation) 800 to 1,000 egg masses per acre, and recreational activities might use the same threshold guidelines as nuisance spray programs. Thresholds for control methods other than aerial spraying would probably be lower than these levels because they are designed to work on low-level populations.

These spraying prescriptions need to be carried out only if the egg-mass populations in the stands exceed the threshold levels for the management objectives of the stands. If the thresholds are not exceeded, then the stands probably will not be defoliated severely enough to cause problems. An exception would occur when the population was supplemented by a large number of larvae invading from adjacent stands. Therefore, if surrounding stands have high population levels, it would be prudent to spray these stands. An excellent example is a lower slope stand with 500 egg masses per acre adjacent to a ridgetop stand with 10,000 egg masses per acre.

While these prescriptions refer to aerial spraying of insecticides as the primary, economical population control technique (Hicks and others 1989), a number of other methods could be used individually or in combination if they become technically and economically feasible. These techniques include parasite establishment and augmentation, microbial application to egg masses, introduction of fungal pathogens and microsporidia, mating disruption using sex pheromones, and inherited sterility techniques (Doane and McManus 1981). All of these control treatments require the designation of a threshold (minimum) population level for initiation of the treatment. Some of them also have an upper threshold limit, where treatments would not be effective on popultions exceeding that limit.

Stand Value

Priority of protection is based on the stand value (7) as determined by the landowner's management objectives. The term, hazard as defined above, is another way of looking at the influence of damage on the value of meeting management objectives. A higher priority for protection would be placed on a high-value stand than on stands of lower value. Stand value can be based on timber, recreation, aesthetic, wildlife habitat, and so on, or a combination of these based upon the management objectives and how severely these objectives would be affected by defoliation and subsequent mortality. Timber values can be determined from local stumpage prices or by conversion value tables (DeBald and Dale 1991; DeBald and Mendel 1976; Mendel and others 1976).

Stand Condition

The vigor or health of a stand (8) influences its response to defoliation. Activities such as drought, frost, ice storms, fire, previous defoliations, cutting, slash disposal, and other disturbances stress the stand. A stressed stand will usually suffer higher mortality than an unstressed stand, so recently stressed stands are high risk. Stands recover from stresses over time. Recovery from some stresses such as thinning or drought may occur in only 1 to 3 years, while others, such as defoliation, may require longer periods (up to 10 years). A compromise value of stress within the last 5 years has been used to separate these higher risk stands from lower risk ones to establish priorities for insecticidal protection.

Stand Mortality

To calculate stand mortality (9), the relative stand density (basal area can be used instead) of dead trees is divided by the sum of stand density of live and dead trees and multiplied by 100. This percentage is used to determine if sufficient volume is present for salvage cutting.

Stand Prescriptions

To develop a stand prescription, decide which silvicultural treatment should be applied in a stand to achieve the landowner's management objectives and prepare detailed instructions for implementing the treatment. Many of the silvicultural treatments presented here are based on a study of forest management considerations of dieback and decline diseases (Houston 1981a) and research on silvicultural treatments to control the gypsy moth (Gottschalk 1982).

Presalvage Thinning

Presalvage thinning (A) is designed to reduce damage by removing highly vulnerable (high hazard) trees (Smith 1962) before they are defoliated and die; the major objective is to reduce stand vulnerability. Secondary objectives of the treatment are to increase stand and tree vigor (and crown condition), to remove structural features or refuges for gypsy moth larvae and pupae, and to promote predator and parasite habitat.

Consider presalvage thinning for stands with greater than C-level density of acceptable growing stock that are more than 15 years from maturity and have more than 80 percent relative density. Under normal management, they would receive a commercial thinning from below. The commercial thinning would reduce relative stand density to 60 percent, but not remove more than 35 percent in any one cut. It should remove unacceptable growing stock, harvest anticipated mortality, increase the growing space for residual trees, and decrease the rotation length. The result is an increase in average stand diameter, a reduction in rotation length, and an improvement in stand quality and value. However, under management taking potential gypsy

moth defoliation into account, the normal prescription must be altered slightly. In stands with more than 50 percent of their basal area in gypsy moth-preferred food species, normal thinning prescriptions will not reduce the preferred food species enough to significantly change the stand's susceptibility. Presalvage thinning concentrates on reducing vulnerability.

It is necessary to implement presalvage thinning 1 to 3 years before defoliation because the stand needs time to recover from the stress and disturbance caused by the thinning. Recovery periods can be from 1 to 5 years (Graney 1987), but recent work has shown that thinning stress does not contribute to increased mortality within a 1- to 3-year period as well as longer time periods.[1] If gypsy moth infestation should occur before this recovery is completed, the stand will be at a higher risk and will need to be protected (see Spray Priority 2 prescription). As part of the stress induced by thinning, stands may be temporarily disposed to attack by certain damaging agents. However, these harmful effects are gradually reduced by the increased tree growth and vigor that occur eventually (Smith 1962). Another potential disadvantage of presalvage thinning is that it may provide favorable conditions for increasing populations of shoestring root rot and twolined chestnut borer (Houston 1981a,c). The longevity of these increased secondary organism populations in the stand is unknown, but if it exceeds 1 to 3 years, then the thinned stand will have a higher risk when it is defoliated.

Figure 9 depicts before and after examples of a presalvage thinning in an older stand while Figure 10 depicts a young stand. Priorities for marking trees to be removed are (highest to lowest): 1) oaks with poor crowns, 2) non-oak species with poor crowns, 3) oaks with fair crowns, and 4) non-oak species with fair crowns. These priorities are integrated with the normal marking priorities of maintaining the desired residual stand density, removing unacceptable growing stock trees before better quality trees (also could include species priorities), and achieving the desired stand structure. Additional measures could be taken to enhance predator and

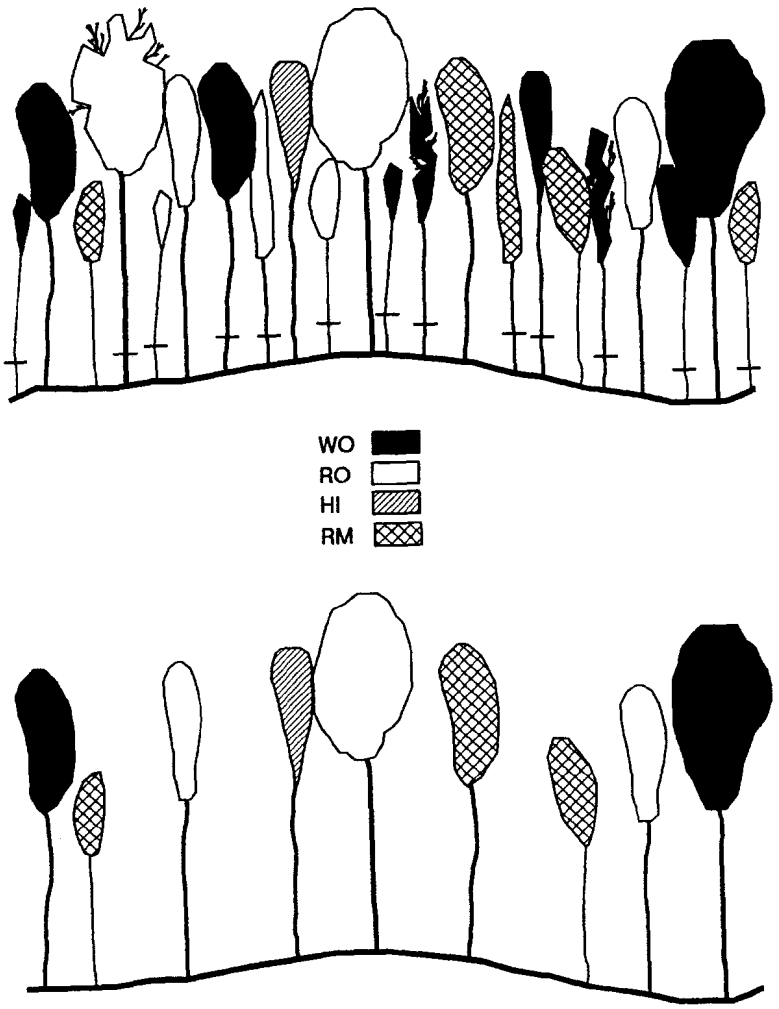


Figure 9.—Presalvage thinning in an older stand showing marking priorites (–) before and result of thinning afterwards (WO = white oak, RO = northern red oak, HI = Hickory spp., RM = red maple).

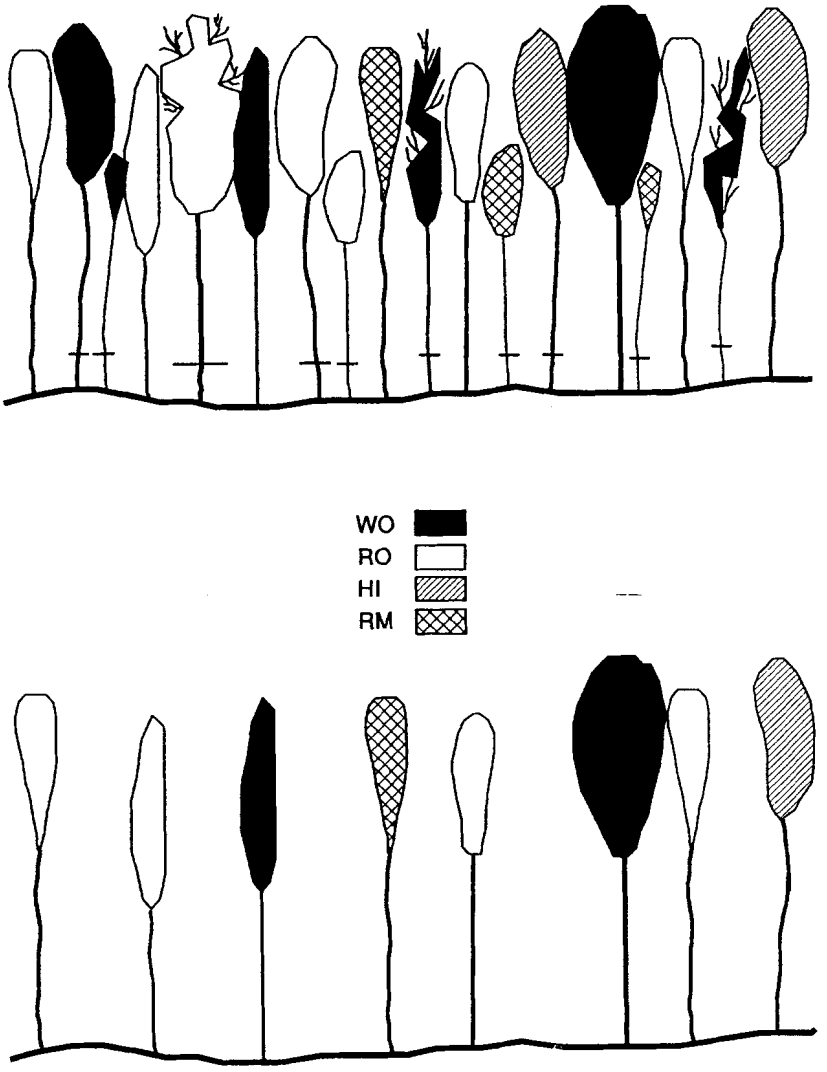


Figure 10.—Before and after scenes of a presalvage thinning in a younger stand (WO = white oak, RO = northern red oak, HI = hickory spp., RM = red maple).

parasite habitat, such as removing trees with abundant structural features or refuges for larvae, leaving snags, leaving cavity or den trees, and creating brush piles. Heavily overstocked stands may have a few good crowns; in this situation, light thinnings to develop and build crowns are called for rather than a heavy thinning.

A recent West Virginia demonstration stand received a presalvage thinning. The estimated stand susceptibility and stand vulnerability before and after treatment were:

	Before treatment	*After treatment*
Susceptibility	high	high
Vulnerability	moderate	low

This treatment accomplished the objective of reducing the vulnerability of the stand, but did not change the susceptibility (Atkins 1989).

Sanitation Thinning

Sanitation thinning (B) is designed to prevent the spread and establishment of damaging organisms (Smith 1962); as opposed to presalvage thinning, the major objective is to reduce stand susceptibility. Sanitation thinning is accomplished by eliminating trees that are current or prospective sources of infestation. With gypsy moth, this process entails removing preferred food species, removing structural features or refuges, and promoting predator and parasite habitat. Secondary objectives are to increase stand and tree vigor, and to remove high-hazard trees. The same precautions on timing and secondary organisms given for presalvage thinning are appropriate here.

Stands that can be considered for sanitation thinning are similar to those considered for presalvage thinning. The major difference is that these stands have less than 50 percent of their basal area in preferred food species, so it is

possible to reduce this percentage enough to change stand susceptibility. There is some evidence that a minimum of 15 to 20 percent basal area of preferred food species is required for a sufficiently large gypsy moth population to develop to the stage where they can survive on nonpreferred hosts. Reducing the percentage of preferred food species to 15 to 20 percent or less, should make the stand less susceptible to defoliation (Burgess and Rogers 1913; Herrick and Gansner 1986). The landowner or manager should realize that this treatment may reduce the stand value considerably since the white and red oaks that would be removed are often the most valuable species in the stand. Of course, some oaks and other preferred species can be retained, but it is still possible that they will be heavily defoliated even though the stand as a whole is only lightly defoliated.

Figures 11 and 12 show the shift in species composition away from oak by sanitation thinnings in older and younger stands, respectively. Priorities for marking trees to be removed are (highest to lowest): 1) **preferred food species,** 2) trees with abundant structural features or refuges for larvae, 3) trees with poor crowns, and 4) trees with fair crowns.

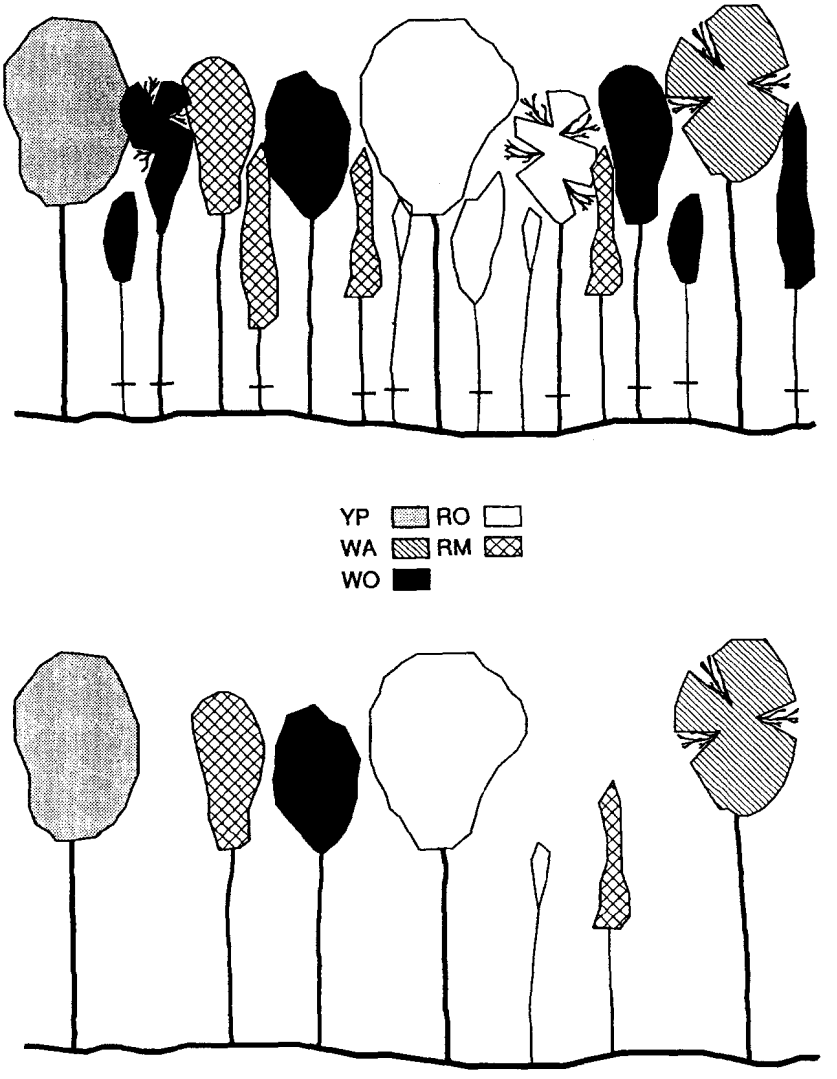


Figure 11.—Sanitation thinning in an older stand showing the shift in species composition from a mixed stand to a predominantly non-oak stand. Note the retention of poorer crown condition immune species over better crown condition susceptible species (YP = yellow-poplar, WA = white ash, WO = white oak, RO = northern red oak, RM = red maple).

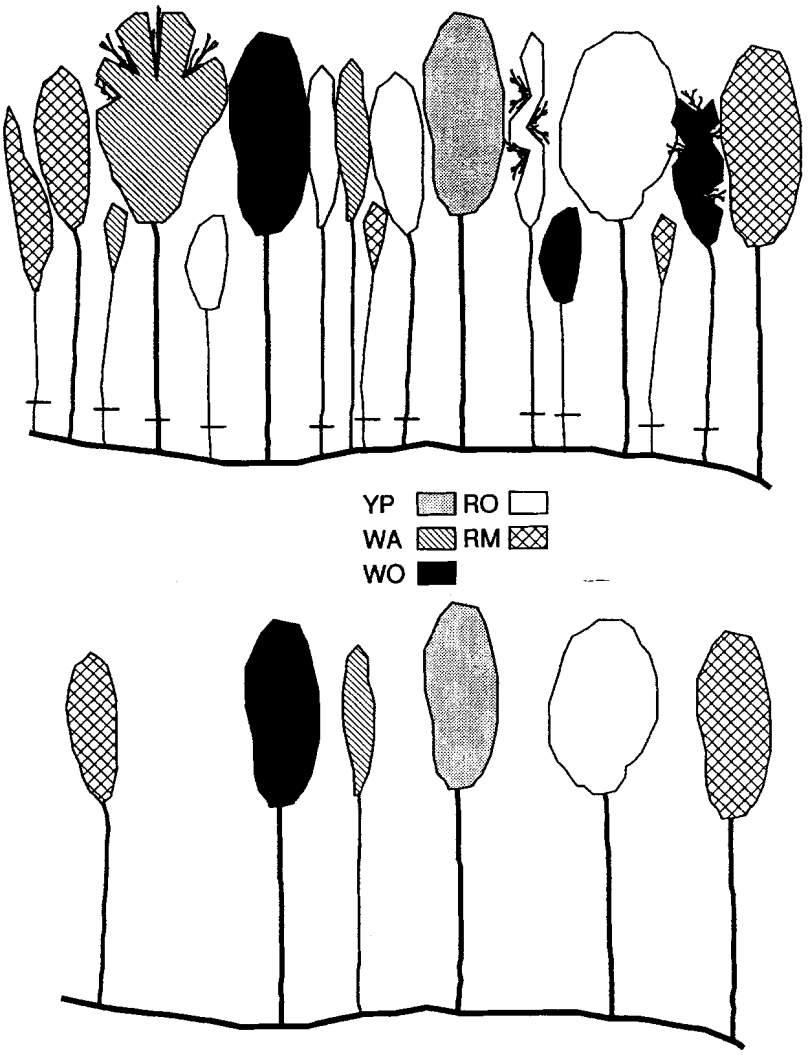


Figure 12.—Before and after scenes of a sanitation thinning in a younger stand (YP = yellow-poplar, WA = white ash, WO = white oak, RO = northern red oak, RM = red maple).

Recently, a West Virginia demonstration stand was established with a sanitation thinning treatment (Atkins 1989). The estimated stand susceptibility and stand vulnernability before and after treatment were:

	Before treatment	*After treatment*
Susceptibility	moderate	low
Vulnerability	high	high

This treatment accomplished the objective of reducing the estimated susceptibility of the stand, but did not change the vulnerability.

Defer Cutting 10 to 15 Years or Re-examine

Management to minimize gypsy moth impact would suggest re-examining these stands (C) for potential control actions if defoliation becomes imminent, for salvage if defoliation occurred, or for thinning once stand density increased without defoliation. These stands also have greater than C-level density of acceptable growing stock and are more than 15 years from maturity. However, they have less than 80 percent relative stand density, so they do not need to be thinned at this time. Normal management would defer cutting for 10 to 15 years or until the density is more than 80 percent.

Defer Cutting 6 to 15 Years or Re-examine

As in the preceding prescription, the only modification for reducing gypsy moth impacts would be to re-examine these stands (D) for potential control actions or regeneration cuttings if defoliation becomes imminent. These stands are adequately stocked but are 6 to 15 years from maturity. It is not desirable to thin them now and harvest a few years later, so the proper prescription is to defer cutting until the stands are mature.

Presalvage Harvest

The primary objective of presalvage harvest (E) is to harvest the stand before defoliation in order to use the adequate advanced regeneration present and preserve stump sprouting. The new stand may be similar in composition to the previous stand or may differ if the advanced regeneration is different and satisfies management objectives. These stands are within 5 years of maturity, or have an unacceptable (less than C-level) density of acceptable growing stock.

Presalvage Shelterwood

Since advanced regeneration and stump sprouting potential stockings are not adequate, the primary objective is to develop adequate regeneration by shelterwood cutting (F) (Loftis 1983a,b; Sander 1979) (Fig. 13). If a large number of undesirable understory woody stems or herbaceous plant cover are present, it may be necessary to control them before the shelterwood cut (Gottschalk 1983, Loftis 1985). Selection of trees to be left in the residual stand should be based on seed productivity, species desired, crown condition, and spacing. The species composition of the residual stand may be shifted by the shelterwood cut if desired. When advanced regeneration stocking becomes adequate, usually in 5 to 7 years (although oaks may take longer), the residual trees can be removed.

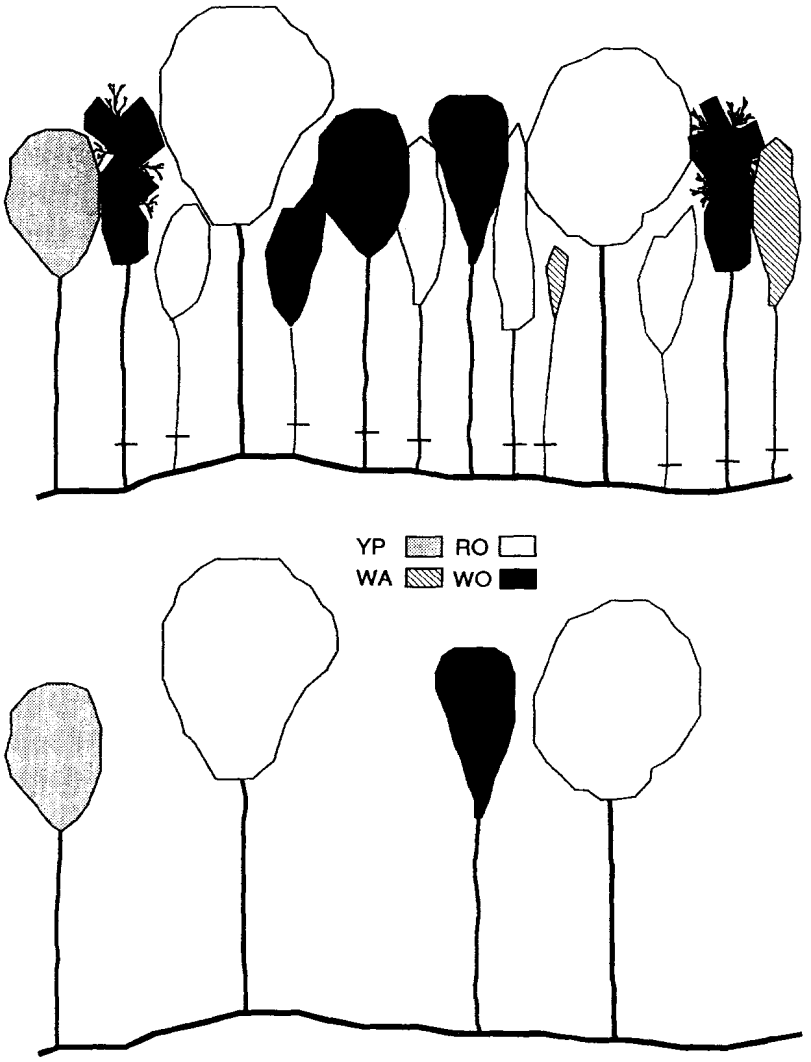


Figure 13.—Before and after scenes of presalvage shelterwood cut. This cut leaves good crowned trees for seed production and will shift species composition to a mixed stand due to retention of seed trees of non-preferred hosts with some oaks (YP = yellow-poplar, WA = white ash, WO = white oak, RO = northern red oak).

Sanitation Conversion

The primary objective is to reduce susceptibility and/or vulnerability by conversion of these stands (G) away from preferred species before infestation by the gypsy moth. Because of high susceptibility or vulnerability, these stands will have either frequent, high defoliation levels or high mortality levels. Low-quality sites could be converted naturally to pines such as white, Virginia, and pitch or artificially to pitch-loblolly hybrids and other conifers (Fig. 14). High-quality sites could be converted naturally to mixed hardwoods, white pine, hemlock, or northern hardwoods (Fig. 15). Shelterwood cutting may be necessary to obtain adequate advanced regeneration with either natural conversion strategy, while artificial conversion may involve substantial costs. Conversion of mixed-oak stands to other species may be economically undesirable because oaks are often the most valuable species that grow on these sites. On the other hand, conversion may be more economically desirable in the long run, because of fewer impacts on the stands from the gypsy moth and lower or no costs for stand protection.

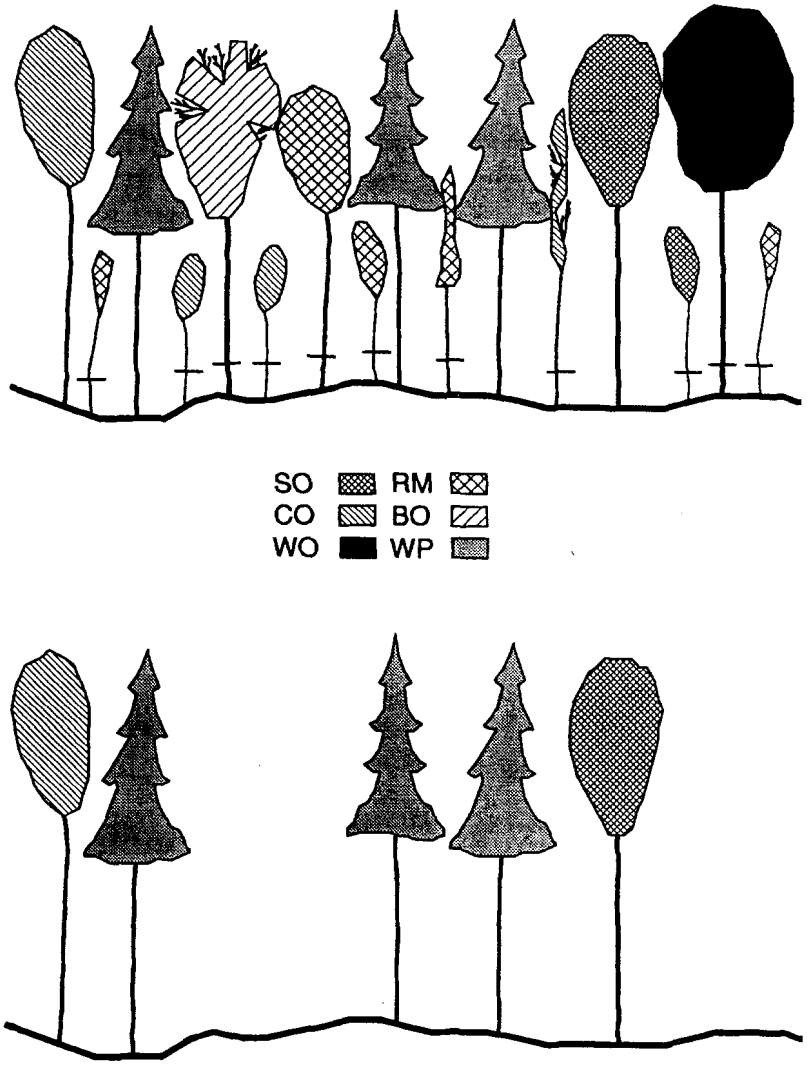


Figure 14.—Sanitation conversion to white pine on lower quality site. Conversion is being done in stages through a shelterwood cut (SO = scarlet oak, CO = chestnut oak, WO = white oak, RM = red maple, BO = black oak, WP = white pine).

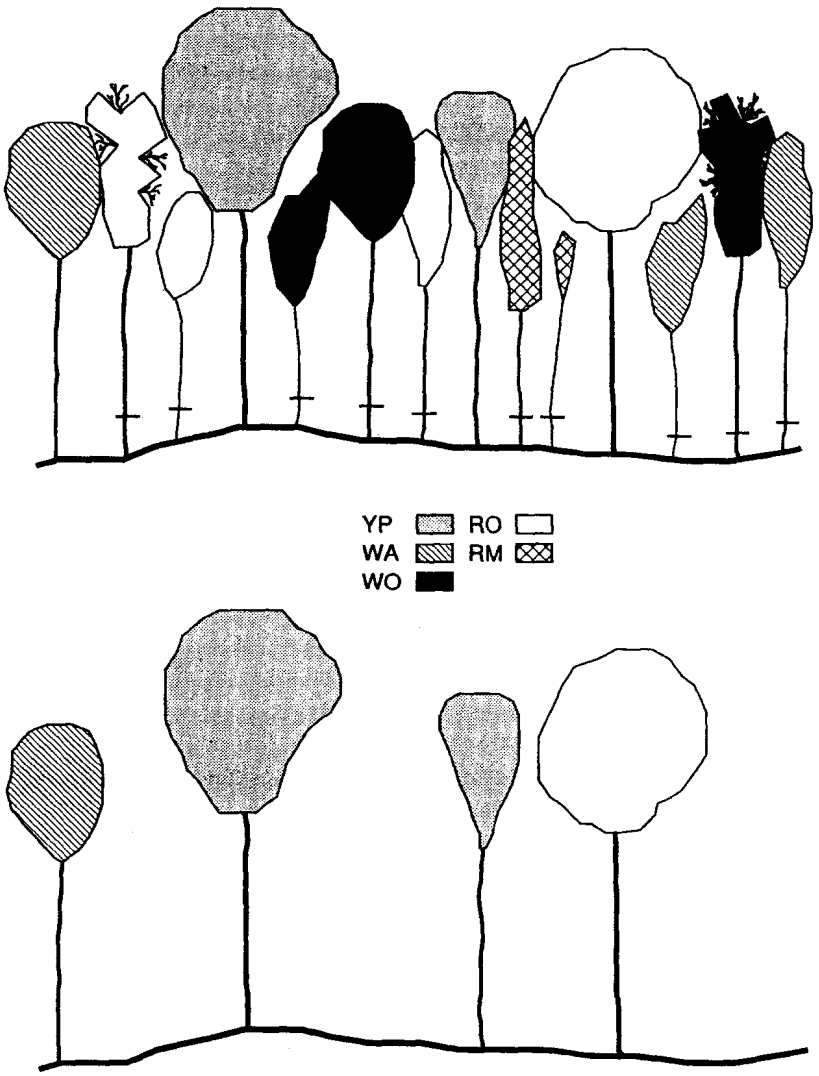


Figure 15.—On higher quality sites, conversion to non-preferred hardwoods with some oaks can be accomplished with a shelterwood cut (YP = yellow-poplar, WA = white ash, WO = white oak, RO = northern red oak, RM = red maple).

Spray Priority 2

Under certain circumstances of high vulnerability, high value (hazard), and high risk, the proper prescription is to aerially spray (H) these stands with an insecticide to protect the foliage. Stands that qualify are more than 10 years from maturity, have had some type of stress or disturbance in the last 5 years, and have a high stand value for meeting management objectives (high hazard). These stands are too far from maturity to harvest, but the stress or disturbance has temporarily made them more vulnerable. High stand value means that there is a greater danger to management objectives in allowing these stands to be defoliated. A high risk means that gypsy moth populations exceed the threshold for treatment based on management objectives of the stand. When prioritizing stands to spray, these stands rank second in importance only behind stands that have been shelterwood cut within 5 years of defoliation (Spray Priority 1). Spraying to prevent timber value losses is an economically feasible treatment in oak stands (Gansner and Herrick 1987a; Hicks and others 1989). Evaluation of benefits other than timber value have not been done, but would likely be feasible as well.

Spray Priority 3

Stands that meet the criteria for this prescription (I) should receive priority spraying after all priority 1 and 2 stands are treated if egg-mass thresholds are reached (high risk). If the landowner exhausted treatment funds before spraying these areas, the stands should be re-examined after defoliation for salvage potential. These stands are more than 10 years from maturity, have not been stressed or disturbed in the last 5 years, and have high stand value for meeting management objectives. While they are not close to maturity, they have not been made more vulnerable by stress or disturbance. With their high value (hazard) and high risk, these stands have less priority than Spray Priority 2 stands due to their lower vulnerability.

Spray Priority 4 or Re-examine

Stands meeting these criteria (J) should be sprayed only after all priority 1, 2, and 3 stands are sprayed and if the egg-mass thresholds are reached. If the stands cannot be sprayed, they should be re-examined after defoliation for potential salvage of dead trees. These stands are similar in maturity and stand condition to those in Spray Priority 2. However, the stand values (hazard) for meeting management objectives are low, so the aerial spray priority of these stands ranks fourth.

Re-examine Stand

The proper prescription for the stands described here is to re-examine them (K) after defoliation to determine their salvage potential. These stands are similar in maturity and condition to those in Spray Priority 3, but their stand values (hazard) for meeting management objectives are low. These stands have very small risk of loss and, therefore, should not be treated.

When gypsy moth populations do not exceed the population threshold for treatment, they should be re-examined (L) by monitoring population levels until thresholds are exceeded or imminent danger of an outbreak has passed. If these stands are not sprayed, they should be re-examined after defoliation to determine their salvage potential.

Presalvage Harvest

This prescription (E, Fig. 1B) is the same as the one in Figure 1A with the same name. However, since these stands are within 10 years of maturity and defoliation is imminent, they should be harvested before defoliation or as soon as possible if defoliation is underway. The landowner is facing a tradeoff between harvesting the stand a few years early and allowing retention of the stump sprouting potential needed to regenerate oaks on the site or allowing defoliation and subsequent mortality to occur which would result in loss of stumpage value and stump sprouting.

Presalvage Shelterwood with Spray Priority 1

This prescription (M) has the same objectives and requirements as the presalvage shelterwood described before (F), however, since the cutting stress on these stands has temporarily predisposed them to higher vulnerability, and the investment in preserving seed production and stump sprouting potential in order to obtain adequate regeneration is high, these stands are the highest priority for foliage protection by aerial spraying (Fig. 16). If population control thresholds are exceeded, these stands must be protected.

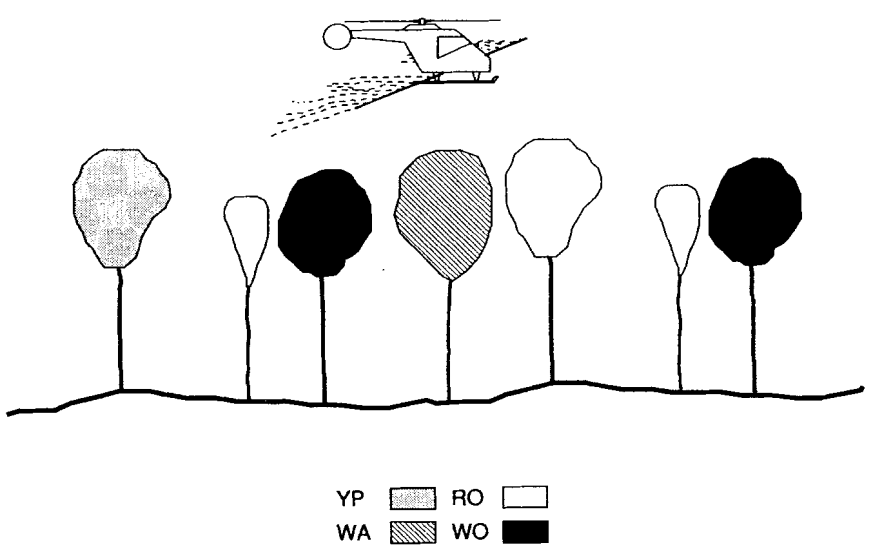


Figure 16.—Presalvage shelterwoods cut within 3 years of defoliation need to be protected with aerial sprays to preserve the investment in regenerating them (YP = yellow-poplar, WA = white ash, WO = white oak, RO = northern red oak.)

Sanitation Conversion

This prescription (G, Fig. 1B) is the same as the one in Figure 1A with the same name. Since defoliation is imminent, the conversion should be done before defoliation if possible, or as soon as possible after defoliation in order to take advantage of any stump sprouting or other regeneration that may be present or to prevent the mortality of conifers that will be used in natural conversion.

Salvage Thinning

With salvage thinning (N), the economic value from the dead trees is salvaged and the remaining live trees are thinned to reduce susceptibility and vulnerability. Stands that qualify for salvage thinning have greater than C-level density of acceptable growing stock, are more than 10 years from maturity, and have greater than 60 percent stand density in live trees. They are sufficiently well stocked to be managed to maturity. These thinnings will improve stand vigor, growth, and quality, and could make the salvage cut economically feasible by supplementing the volume of dead trees with green trees. They should remove no more than 35 percent stocking of live trees in any one cut, while reducing relative stand density to 60 percent. If defoliation is then imminent within 1 to 3 years, following the salvage thinning, the stands will have been stressed by the cutting and may need to be sprayed. On the other hand, mortality probably has resulted in less susceptible and less vulnerable stands than were present before the previous defoliation.

Examples of salvage thinnings in older and younger stands are shown in Figures 17 and 18. Priorities for marking trees

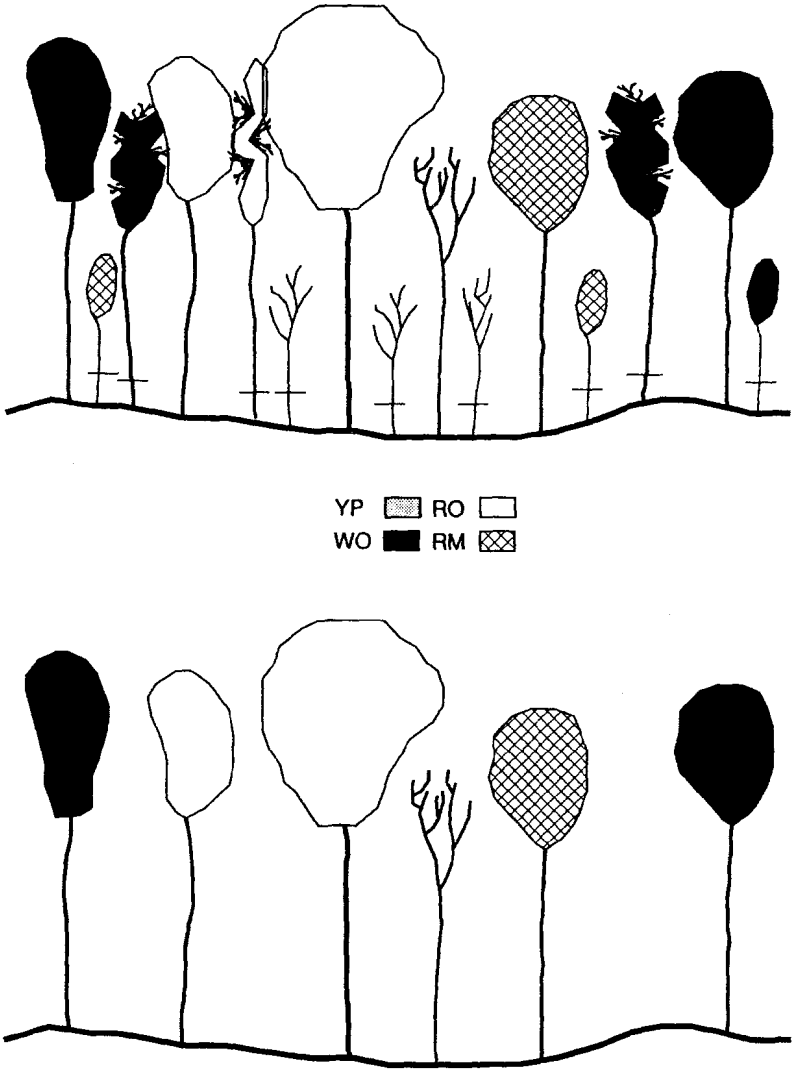


Figure 17.—Salvage thinning in an older stand showing removal of dead trees and live trees, especially those in poor crown condition. Note retention of snag for wildlife and predator habitat (YP = yellow-poplar, WO = white oak, RO = northern red oak, RM = red maple).

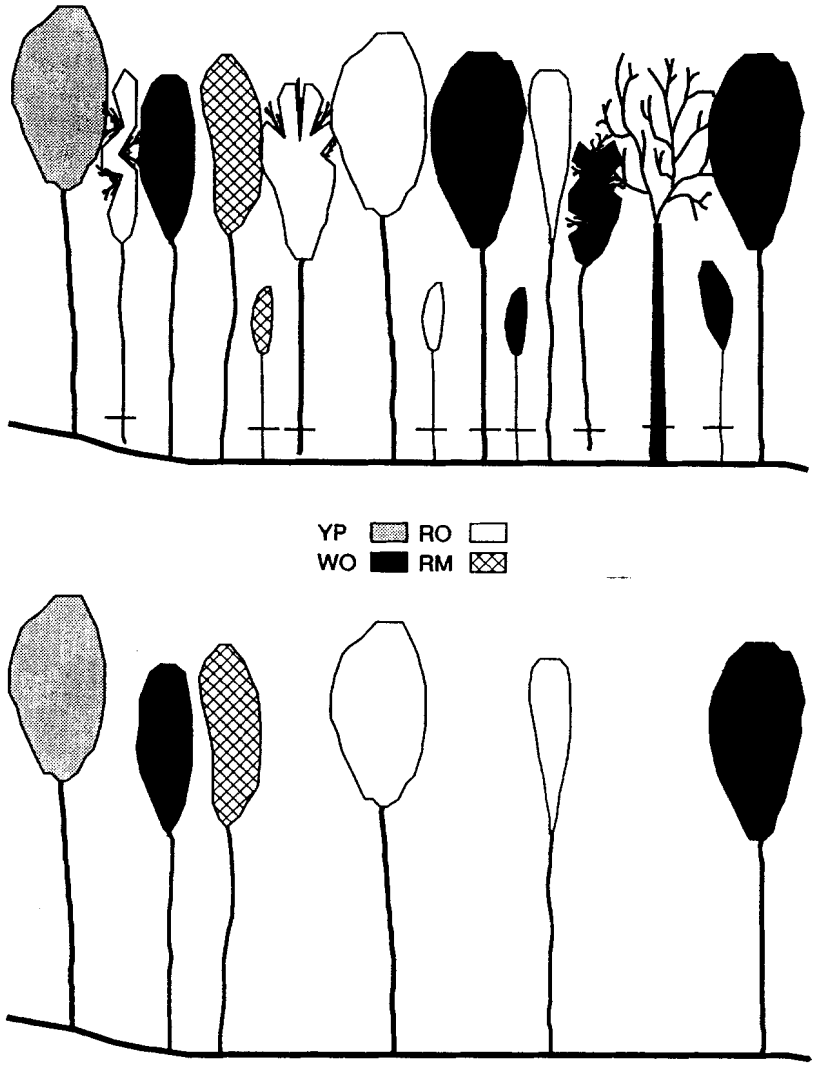


Figure 18.—In younger stands, salvage thinnings remove dead trees, live trees in poor crown condition, and other live trees (YP = yellow-poplar, WO = white oak, RO = northern red oak, RM = red maple).

to be removed are (highest to lowest): 1) dead trees, 2) oaks with poor crowns that are likely to die, 3) other species with poor crowns that are likely to die, and 4) trees with fair crowns. These priorities are integrated with the normal ones of maintaining the desired residual stand density, removing unacceptable growing stock trees before better quality trees, and achieving the desired stand structure. It is desirable to leave several dead trees per acre as snags, cavity, or den trees, and to remove trees with structural features or refuges for larvae.

A demonstration salvage thinning was conducted in West Virginia recently. The estimated stand susceptibility and stand vulnerability before and after treatment were:

	Before treatment	*After treatment*
Susceptibility	moderate	moderate
Vulnerability	moderate	low

In addition to reducing the future estimated vulnerability of this stand, dead trees (7 percent of the stand) were economically salvaged, mature trees were thinned, poor-crowned trees as a result of the defoliation were thinned, and the landowner received more income for this treatment than a local logger had offered to liquidate the entire stand (Atkins, 1989).

Salvage Cutting

The objective in stands that qualify for this treatment (O) is to economically salvage dead and dying trees. These stands are similar in acceptable growing stock density and stand maturity to the stands in the preceding prescription, but have less than 60 percent stand density in live trees. In this situation, no thinning of live trees is necessary since density is already below the optimum residual density. They also have greater than 30 percent mortality which means that there is sufficient volume and value of dead trees for a salvage cut (depending upon local market conditions). Marking priorities are simple—only dead and dying trees should be cut and removed because all of the live trees are needed to carry the stand to maturity (or to the next thinning) (Figs. 19 and 20). Trees with very poor crowns that will not recover are considered the same as dead. These dying trees are removed and not counted toward the acceptable growing stock density. If desired, several dead trees per acre could be left as snags. Because of the mortality that has occurred, the residual stand is probably less susceptible and less vulnerable than before the previous defoliation.

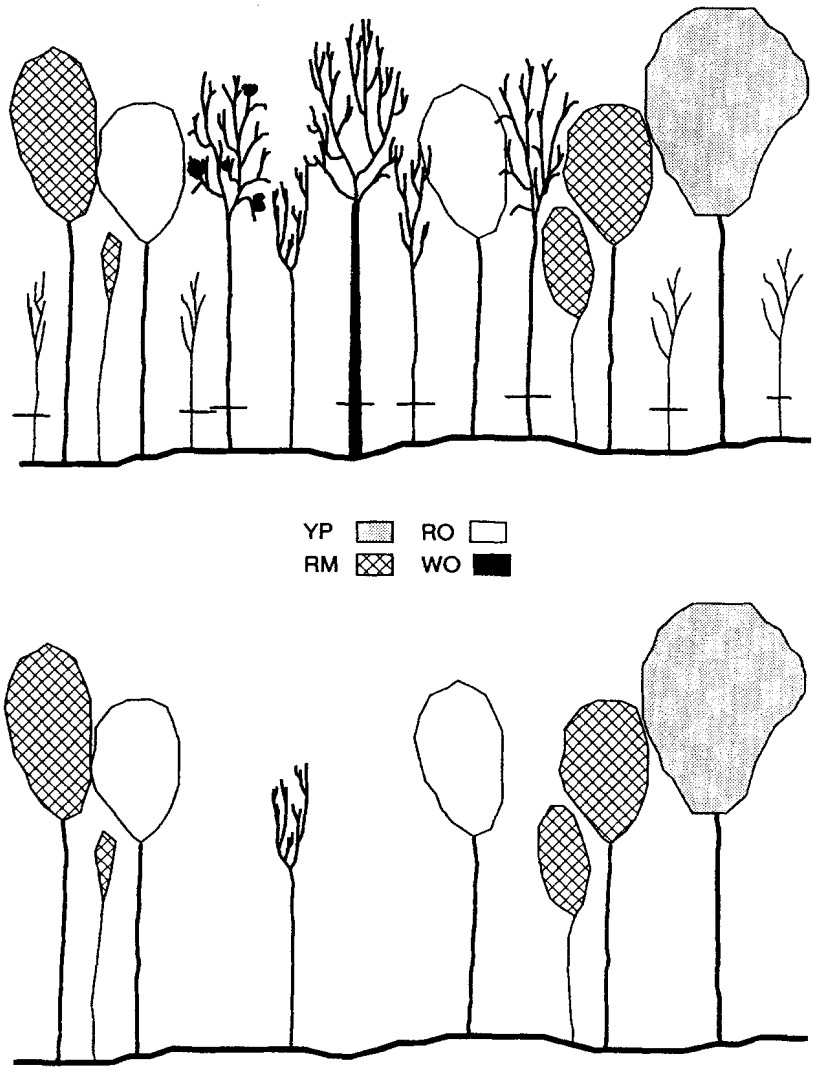


Figure 19.—Salvage cutting in an older stand removes only dead trees and very poor condition live trees. Note snag retention for wildlife and predator habitat (YP = yellow-poplar, WO = white oak, RO = northern red oak, RM = red maple).

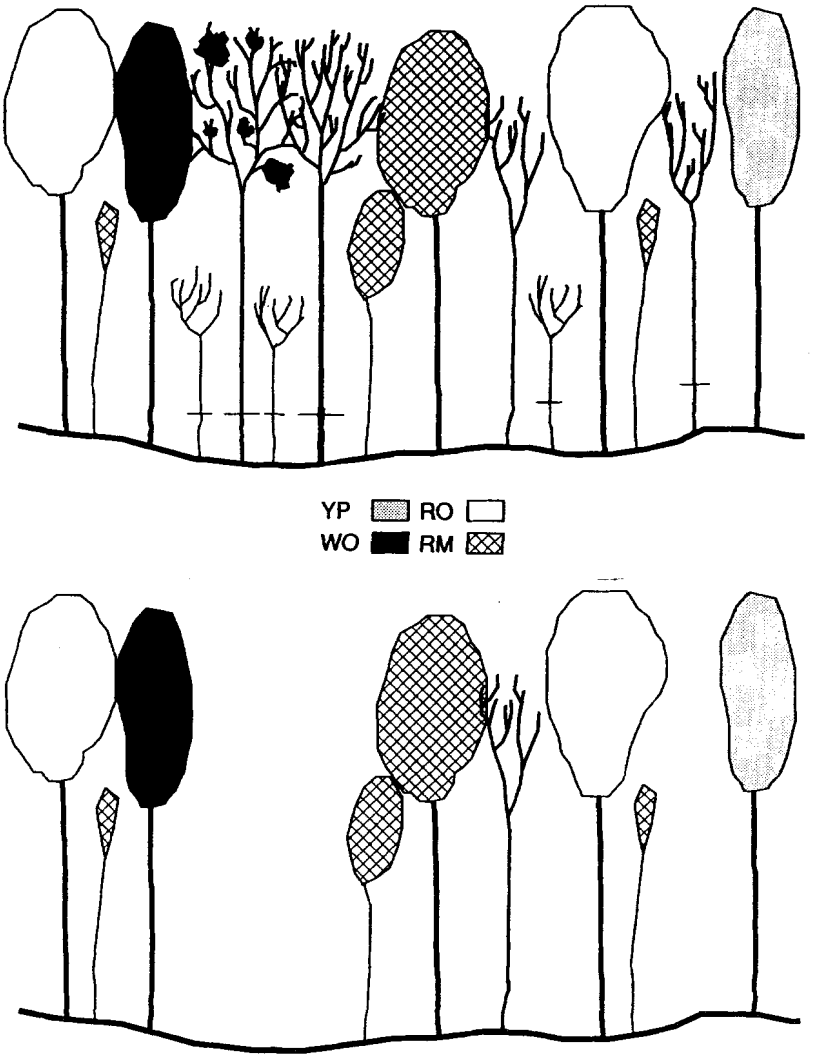


Figure 20.—In younger stands, salvage cutting removes dead trees and very poor condition live trees. Note snag retention for wildlife and predator habitat (YP = yellow-poplar, WO = white oak, RO = northern red oak, RM = red maple).

Defer Cutting

Stands that qualify for this treatment (P) probably do not have sufficient volume and value of dead trees for an economically feasible salvage cut. And, since live trees cannot be cut, the proper prescription is to defer cutting until the stands can be thinned or re-examined if defoliation becomes imminent. These stands are similar to those in the preceding prescription in their characteristics except that mortality is less than 30 percent. In areas with very good markets, it may be possible to economically salvage some of these stands. For stands with good access, an alternative may be to salvage some or all of the dead trees for firewood. The residual stands are probably less susceptible and less vulnerable than before the previous defoliation due to the mortality that has occurred.

Salvage Harvest

The primary objectives of salvage harvest (Q) are to salvage economic value from dead trees and to bring the stand back into production utilizing the adequate advanced regeneration stocking and stump sprouting potentials that are present. These stands are within 10 years of maturity, or have an unacceptable density of acceptable growing stock.

Salvage Shelterwood

The primary objectives of salvage shelterwood (R) are to salvage economic value from dead trees and to develop adequate advanced regeneration by shelterwood cutting. It may be necessary to cut some live trees for the shelterwood in addition to salvaging dead trees (Figs. 21 and 22). The information on shelterwood cutting in the presalvage shelterwood prescription (F) also applies here.

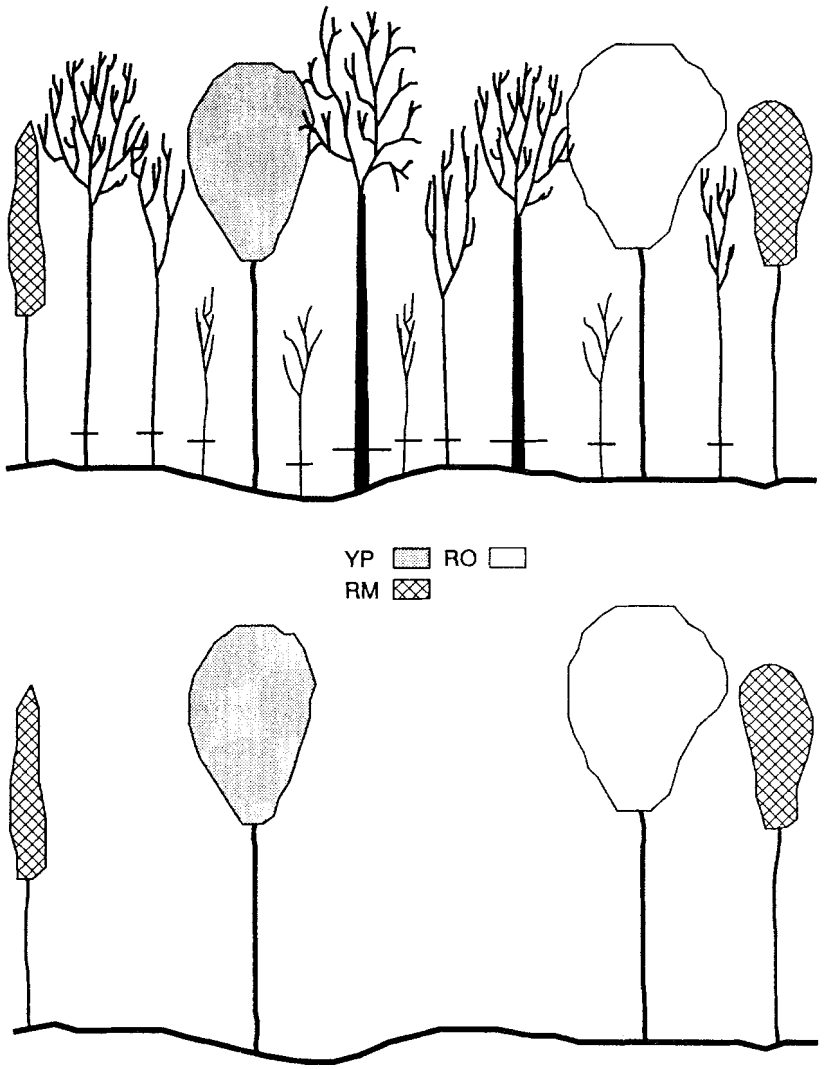


Figure 21.—Salvage shelterwood in older stand leaves trees that will be good seed producers (YP = yellow-poplar, RO = northern red oak, RM = red maple).

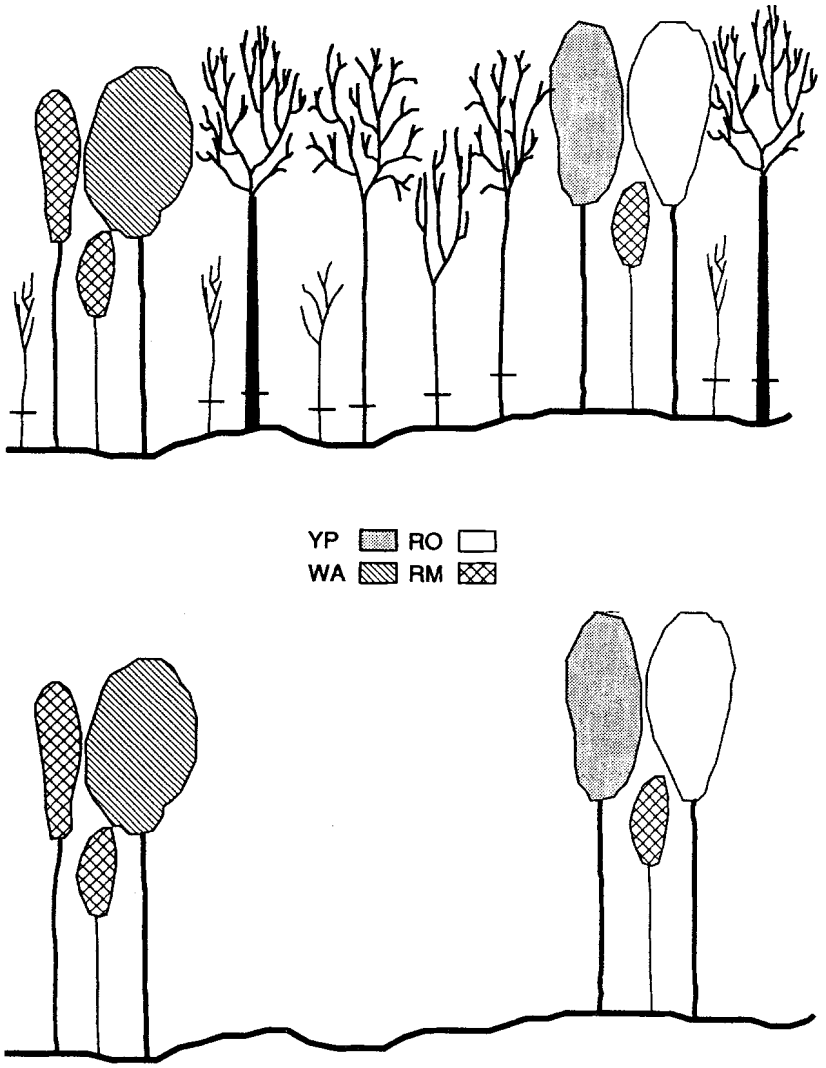


Figure 22.—In younger stands, salvage shelterwoods are used to regenerate the stand prematurely, soon after heavy mortality occurs. Note the large holes that may occur due to the clumpiness of the mortality. In some situations, this cut may be similar to group selection cutting (YP = yellow-poplar, WA = white ash, RO = northern red oak, RM = red maple).

Salvage Conversion

The primary objectives of salvage conversion (S) are to salvage economic value from dead trees and to convert these stands to species not preferred by gypsy moth. The mortality that has occurred may have already contributed to the conversion process by eliminating stump sprouts and seed production of preferred species. The information on conversion in the sanitation conversion prescription (G) applies here also.

Utilization of Dead Trees

For dead trees to be salvaged economically, it is necessary to cut and process the timber rapidly. Once a tree dies, it is attacked by a variety of insects, fungi, and bacteria (Donley and Feicht 1985; Haack and others 1983; Karasevicz 1987; Karasevicz and Merrill 1989) that cause the tree to gradually decay and make it less usable with increasing time after death. The faster a tree can be used after it dies, the more volume and value it will produce. Under the provisions of the Gypsy Moth Quarantine administration by Animal and Plant Health Inspection Service (APHIS), a permit and an inspection often are required to move logs, trees, or firewood from the infested area to uninfested areas. This quarantine is intended to slow down the artificial spread of the gypsy moth.

Sawtimber and Veneer

Sawtimber and veneer are generally the highest value products produced by the stand, so salvage operations should try to minimize their losses. Red and white oak trees that were dead 1 year or less, 2 to 4 years, or 5 years or more were examined for their potential use as lumber (Garges and others 1984; Labosky 1987; Labosky and others 1984). Lumber recovery from these trees decreased by 4 to 8 percent for trees dead 1 year and 20 percent for trees dead 2 years or more. Most of this loss was from sapwood decay (Karasevicz and Merrill 1989; Labosky and others 1990). In addition to less volume recovery, there was a substantial shift in lumber grades recovered; 1 Common and Better grades decreased while 2 and 3 Common grades increased with increasing time after death due to decay, drying checks, and insect borer holes, resulting in substantial value loss. Lumber from trees dead 5 years or more also suffered grade reduction due to checking during kiln drying. These losses could be minimized by using a milk kiln schedule (Dennis and others 1986). Decreases in stumpage value with time after death reflect these volume and value losses (Fig. 23) (Donley and Feicht 1985; Laubach 1982). Veneer users usually will not buy a tree once it is dead due to staining, drying, and checking (Laubach 1982), so death of a veneer tree will result in its being downgraded to sawtimber status. The best salvage period for sawtimber is within the first year after death, which results in negligible losses. Trees can still be salvaged up to 4 to 5 years after death, but with increasing volume and value loss and decreasing stumpage value.

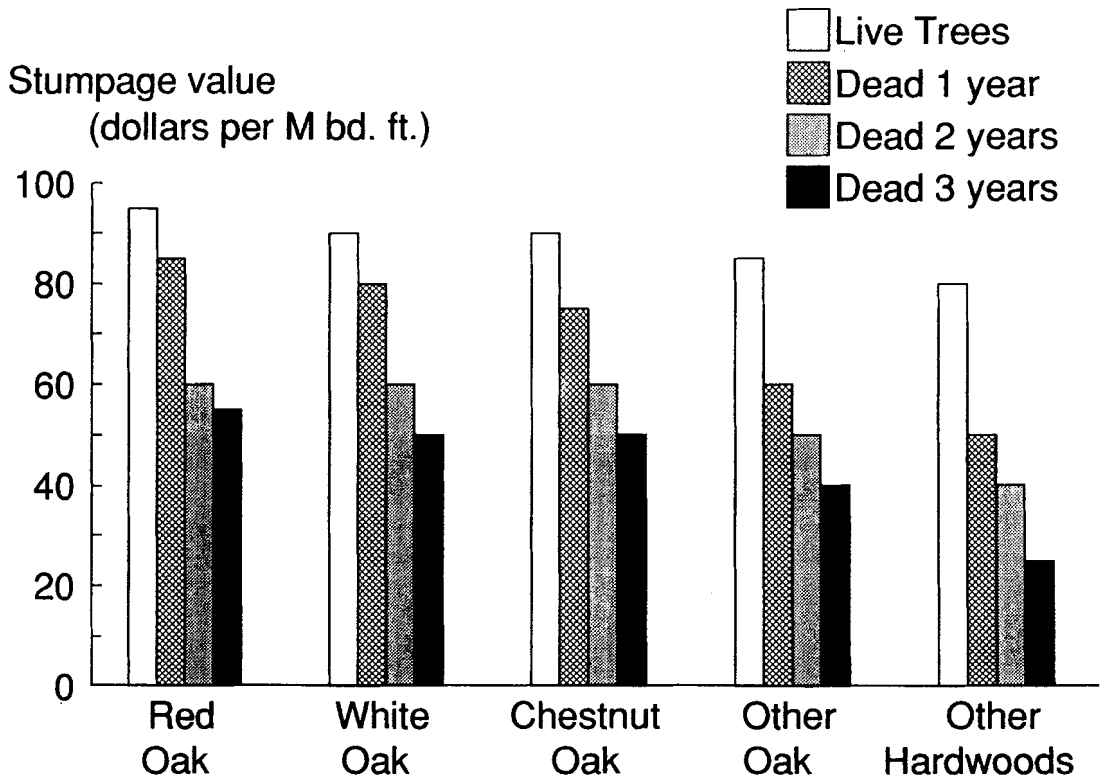


Figure 23.—Change in stumpage value with time after death of oaks and other hardwoods (redrawn from Donley and Feicht 1985).

Pulpwood and Firewood

Dead trees that do not qualify for sawtimber can be salvaged for pulpwood or firewood. Pulping characteristics were examined for trees dead 1 year or less, 2 to 4 years, or 5 years or more (DeCrease and others 1985; Kessler and Labosky 1988; Labosky and Baldwin 1984). Pulp yields were constant and similar to those for green trees for trees dead up to 5 years. Pulp quality decreased slightly after 3 to 4 years, and fiber strength declined slightly after 5 years. There was a decrease in debarking losses and fines and an increase in chip solids up to 3 to 4 years. In many respects, trees that were dead for 1 to 4 years were as good or better than green trees (Kessler and Labosky 1988; Labosky and others 1990). This makes sense when one considers that in the 1950's, pulp and paper companies were injecting trees with sodium arsenate and allowing them to stand dead for a year or two so that the bark would fall off before harvesting. Firewood value also is enhanced by the debarking and drying process that occurs in dead trees. By 5 years after death, caloric value is equal to live trees, but 25 percent of the tree's weight has been lost to decay (Labosky and others 1990). However, this advantage is offset somewhat by the increased danger in felling dead trees.

SILVICAL BACKGROUND

Suggestions for the use of silvicultural treatments to mitigate the impacts of gypsy moth populations were first made at the beginning of this century. Additional interest during the late 1930's and early 1940's resulted in recommendations that centered around reducing the amount of preferred food for gypsy moth in existing stands or changing the species composition to nonpreferred host trees through stand conversion, but they have rarely been applied. There was little interest in the topic for the next few decades, primarily due to the effective aerial use of the chemical insecticide, DDT, against the gypsy moth. However, as restrictions were placed on this control method; the area of gypsy moth impact increased; integrated pest management approaches became popular, and silvicultural treatments attracted interest again. The guidelines presented in the first section of this report incorporate ideas from some of these earlier works. Also, they represent an assimilation of ecological and silvical information on gypsy moth-forest interactions. This assimilation formed the theoretical basis for development of many of the prescriptions. A summary of the assimilation is presented for the reader who would like additional information.

References: Baker and Cline 1936; Behre 1939; Behre and Reineke 1943; Behre and others 1936; Bess and others 1947; Brown and Sheals 1944; Brown and others 1979; Burgess and Rogers 1913; Clement and Munro 1917; Cook and Kreeland 1914; Ėdel'man 1957; Fiske 1913; Forbush and Fernald 1896; Gansner and others 1987; Gottschalk 1982, 1986, 1987, 1989a,b; Gould 1971; Houston 1981a; Korstian and Ruggles 1941; Mason and others 1986; Nichols 1980.

Susceptibility

Susceptibility to defoliation is defined as the likelihood (or probability) of a forest stand being defoliated if an insect population is present (Smith 1962). A stand's susceptibility is determined by species composition, site factors, and stand history. Together these factors contribute to favorable habitat for the gypsy moth and less favorable habitat for its predators and parasites as first described by Bess and others (1947). Susceptible stands are defoliated more frequently than resistant stands and in many years are the only stands supporting a gypsy moth population large enough to cause noticeable defoliation. Stands that are resistant to defoliation are not defoliated or defoliated only in years of epidemic outbreak conditions, especially when they are located adjacent to susceptible stands (Houston and Valentine 1977). It is important to remember that susceptibility and immunity are a continuum with increasing resistance between them. While some stands are clearly susceptible and others are clearly immune; the majority of stands will have a resistance that falls somewhere between these two extremes.

Stand Composition

The single most important factor determining the susceptibility of a stand is its species composition. Mosher (1915) established that gypsy moth larvae favored certain trees and plants over others (Table 1). He found that some species are favored by all larval instars (5 to 6 molting stages in the development of caterpillars) (susceptible in Table 1); that other species are not eaten by young instars (first and second) but might be eaten by later instars (third and higher) (resistant in Table 1); that some species are not particularly favored but may be eaten when favored food is scarce (resistant in Table 1); and that some species are not eaten under any circumstances (immune in Table 1).

Table 1 lists the more common tree and shrub species by three food preference classes. Oak species are highly favored by the gypsy moth. Gansner and Herrick (1985) have documented for central Pennsylvania the 1981 defoliation ratings that reflect gypsy moth food preferences in the field (Fig. 24). Campbell and Sloan (1977c) have similar data from New England for 1911 to 1921, while Fosbroke and Hicks (1989) have data from the Allegheny Plateau in western Pennsylvania for 1987 (Fig. 25). Both data sets support Mosher's classification. Because first-instar gypsy moth larvae must feed on susceptible species to survive (Barbosa and others 1983; Campbell and others 1975a; Campbell and Sloan 1977b), stands that contain little or no susceptible species presumably will not support populations of young larvae and are resistant to defoliation. Conversely, stands with large numbers of susceptible species could support large gypsy moth populations. Individual tree defoliation ratings converted to stand-level averages over a 3-year period in central Pennsylvania show this pattern (Fig. 3) (Herrick and Gansner 1986).

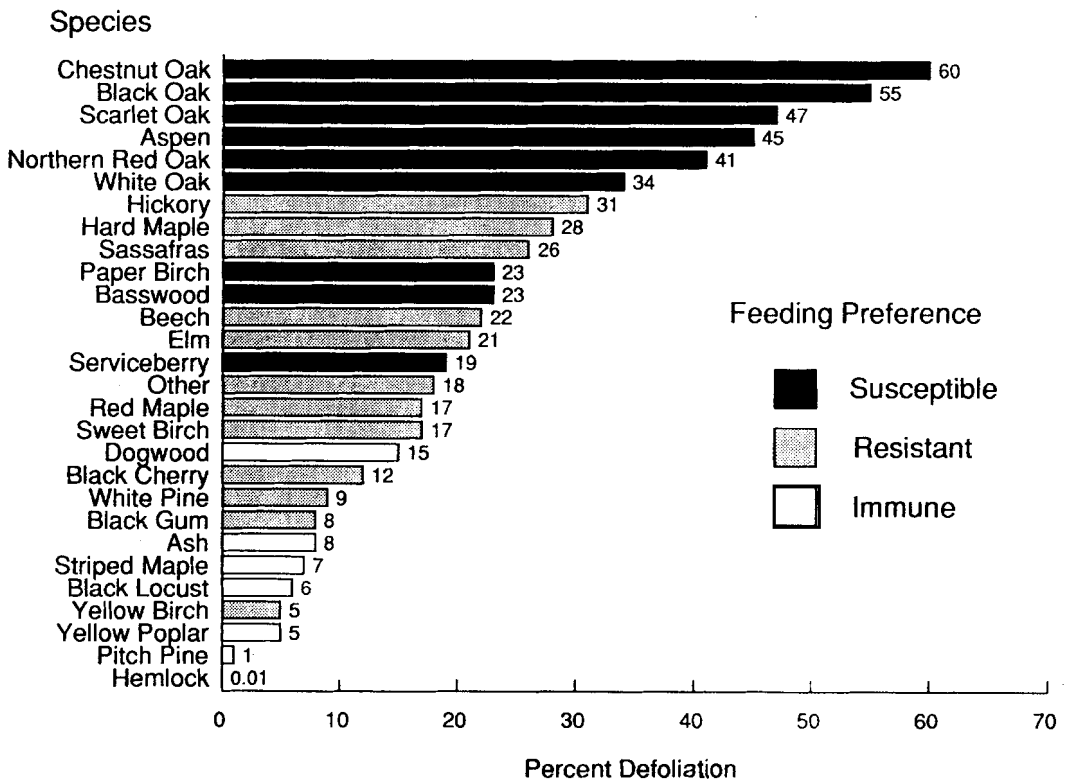


Figure 24.—Average 1981 defoliation by species present on Central Pennsylvania Ridge and Valley plots (redrawn from Gansner and Herrick 1985).

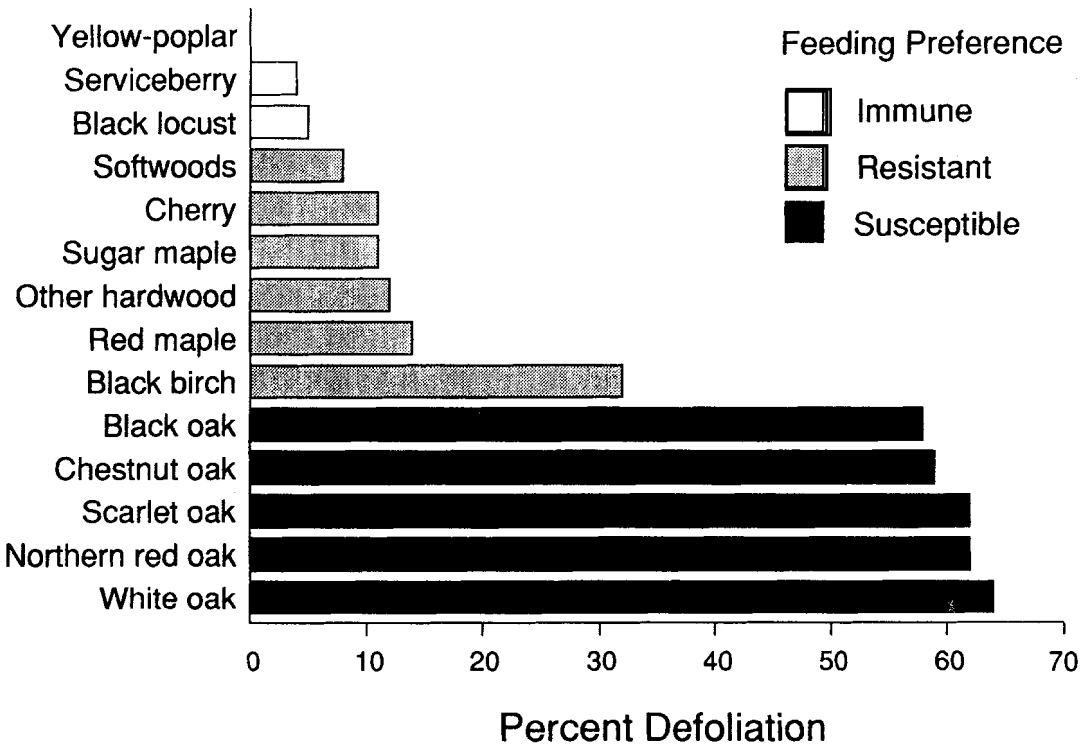


Figure 25.—Average 1986 defoliation by species present on western Pennsylvania Allegheny Plateau plots (redrawn from Fosbroke and Hicks 1989).

The oak-hickory forest type and its variants, which are 46 percent of the 253-million-acre eastern hardwood forest (USDA Forest Service 1990), are prime habitat for the gypsy moth (Fig. 26). This type classification includes a wide variety of specific forest types: upland oaks, mixed hardwoods in the Central and Lake States, and Appalachian mixed hardwoods. The Society of American Foresters (SAF) upland oak forest types (Eyre 1980) would all be classified as medium or high susceptibility. The Appalachian, Central, and Lake States mixed hardwoods are characterized by a large diversity of species. These stands are highly variable in susceptibility. The susceptibility of any one stand depends primarily on the percentage of preferred food species in the stand. A stand with 60 percent preferred food species would have high susceptibility, whereas one with 40 percent would have medium susceptibility, one with 15 percent would be resistant (low susceptibility), and one with no preferred species would be immune to most gypsy moth defoliation (Campbell 1974; Herrick and Gansner 1986). Stands in SAF types 57 yellow-poplar and 58 yellow-poplar—eastern hemlock in particular, as well as other types with few preferred species, are immune to gypsy moth defoliation. Close proximity of a mixed hardwood stand to predominantly oak stands may influence its susceptibility because larvae can disperse from one stand to nearby stands during heavy outbreaks.

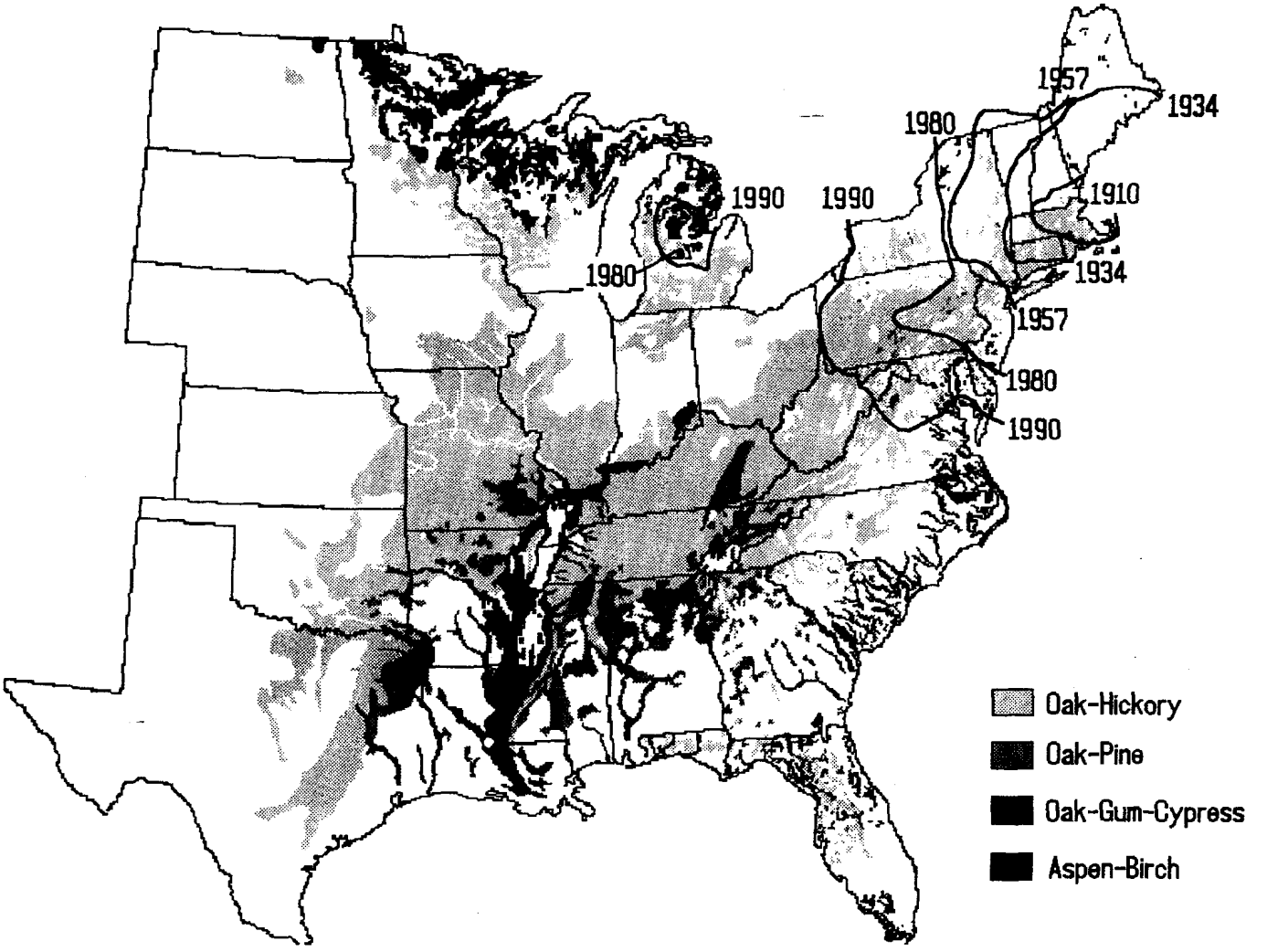


Figure 26.—Map of eastern forest types susceptible to severe gypsy moth outbreaks (redrawn from Eyre 1980) with gypsy moth range expansion.

The oak-pine types (12 percent of the eastern hardwood forest) offer a very interesting situation. The presence of highly preferred oaks ensures that populations will be able to develop during early instars (Montgomery and others 1989). Older larvae have moderate to good development on almost all resistant pine species and therefore they can complete their life cycle on the pine foliage even if all of the preferred foliage is gone. Most oak-pine stands have considerable susceptibility, especially when oak is higher than 40 to 50 percent of the stand. If the pines are completely defoliated, there is a good chance that there will be heavy mortality (Brown and others 1988; Stephens 1988). In many areas of the South SAF types 82 loblolly pine-hardwood and 85 slash pine-hardwood have variable mixtures of oaks, sweetgum, and other hardwoods depending on the moisture regime of the site. Since sweetgum is also a preferred species, mixtures with sizeable amounts of sweetgum and/or oaks would be susceptible while mixtures with broadleaf evergreens (sweetbay, magnolia, redbay), swamp tupelo, and red maple would be resistant. Most forest managers should treat oak-pine stands the same as oak-hickory stands as far as susceptibility is concerned. For further information on silvicultural treatments in oak-pine and pine-hardwood mixtures, consult Gottschalk and Twery (1989).

The oak-gum-cypress types (11 percent of the eastern hardwood forest) have not been tested in terms of their potential susceptibility because gypsy moth is just now reaching stands in this classification. This broad type is a mixture of bottomland types with a wide variance of species. Those SAF types that contain bottomland oaks and sweetgum are good candidates for high susceptibility. The types containing baldcypress, tupelos, sweetbay, and redbay are likely to be resistant or immune. The annual flooding that occurs in these types may have an unknown effect on survival of gypsy moth egg masses and young larvae. It may change larval behavior and predator communities as well. These changes may enhance susceptibility or reduce it. As experience is gained in this type, better classification can be made.

The northern hardwood types of maple-beech-birch and aspen-birch represent 17 and 7 percent of the eastern hardwood forest, respectively. These types are also highly variable in susceptibility. Older, more advanced climax stands are not very susceptible unless they have a large percentage of preferred species mixed in them, as occurs in the oak-northern hardwood transition zone where northern red oak can represent a sizeable portion of the stand. Early successional northern hardwood stands, containing large amounts of aspen, gray birch, and other intolerant preferred species, have higher susceptibilities, but may not suffer extensive mortality. As these stands develop and mature, the intolerant preferred species drop out of the stands, and they become more resistant to defoliation. Bess and others (1947) reported that changes in species composition and stand structure that accompany late successional stages lower susceptibility, while disturbances that set back the successional stage increase susceptibility. SAF type 28 black cherry-maple (Allegheny hardwood type) is composed primarily of resistant species, so it is relatively resistant to defoliation. These stands have the greatest probability of defoliation in the oak-northern hardwood transition zone, where they are intermixed with oak stands or contain a sizeable percentage of oak (usually northern red oak) and other preferred species. The presence of these species allows young larvae to develop to the stage where they can feed on black cherry, and red and sugar maples. The susceptibility of most Allegheny hardwood stands would be rated as low and they would rarely be defoliated by the gypsy moth.

The remaining eastern hardwood type classification is the elm-ash-cottonwood which represents 6 percent of the area. This group of bottomland hardwood types has not been exposed to gypsy moth and should be low in susceptibility or highly resistant due to the high percentage of resistant and immune species contained in them.

The coniferous forest types in both the north and south should be high in resistance due to their inability to support young larvae unless located adjacent to highly susceptible stands or they contain a moderate amount of preferred species mixed in. Southern types with low percentages of oak or sweetgum may experience some defoliation, but should not develop large, devastating populations. Northern types with oak, aspen, or birch in small amounts would be similar. Exceptions would be SAF types 38 tamarack, 20 white pine-northern red oak-red maple, and 51 white pine-chestnut oak, which could reach low to moderate susceptibilities and be subject to occasional defoliations. Further information on these types is available (Gottschalk and Twery 1989; Montgomery and others 1989).

Other Factors

In addition to species composition, susceptible sites are characterized by slow growth, frequent drought stresses, and low foliage biomass. Dry, rocky ridgetops with shallow soils or outwash plains with dry, sandy soils are prime examples of susceptible sites. Larvae in the last three instars seek shelter during the day on refuges such as rock outcroppings, litter, or suitable locations on the tree such as bark flaps, large dead branches, wounds or holes in the bole, dead sprout stubs, deep bark fissures, lower sides of branches, and on trees with crook or sweep (Bess and others 1947; Campbell and others 1975a,b). Disturbances also are common in susceptible stands. Frequent fire, heavy cutting, slash disposal, grazing, windthrow, and ice storm damage are just a few of the disturbances associated with susceptible stands. Slow growth associated with stress and disturbances create abundant refuges for gypsy moth larvae. Man-made refuges such as signs, fences, buildings, and trash also are used by the larvae (Campbell and others 1976).

In low-level populations, survival of late-instar larvae and pupae tends to be greater when they can find refuges off the ground because of less predation by small mammals and other predators and parasites (Bess and others 1947; Campbell 1967; Campbell and Sloan 1976; 1977a,b;

Smith 1985). Removal of natural or man-made refuges (or "structural features" as they have been called) is one technique for reducing favorable gypsy moth habitat in a stand. Susceptible sites had fewer small mammal predators and less desirable habitat than more resistant sites (Yahner and Smith 1991). Providing favorable predator and parasite habitat also should reduce the susceptibility of the stand. However, many refuges for gypsy moth also provide good predator habitat. **The goal should be to reduce gypsy moth refuges that are high in the trees before reducing refuges that are low in the trees or on the ground where they provide predator habitat. This forces the larvae into the open at a level where predators can find them.**

Resistant sites are characterized by straight fast-growing trees with few refuges, deep soils, infrequent drought stress, and higher foliage biomass. Stands that are more mesophytic (wet bottoms, moist slopes, and ridges with favorable moisture regimes) and are rarely disturbed generally are more resistant to gypsy moth defoliation mostly due to species composition.

Periodic environmental stresses such as frost damage or a 2- to 3-year drought often increase stand susceptibility to insect pests (Kulman 1971; Mattson and Haack 1987). Stress and disturbance from thinnings, soil compaction, increased light and moisture levels, and logging damage all require time for the stand to recover. These temporary increases in susceptibility may be due to changes in foliage quantity and quality for gypsy moth. Strips of susceptible forests often are adjacent to housing developments, recreational facilities, roads, rights-of-way, and other areas where human activity is intense. This activity causes disturbances that create refuges and stress the trees (Campbell and other 1976; McManus and others 1979).

Tree Growth Responses to Defoliation

Defoliation reduces the primary leaf area by direct consumption. Secondary leaves produced by refoliation are smaller, chlorotic, fewer in number, and are exposed to frost by remaining on the tree much later in the fall. The effect of defoliation is not limited to the year of actual defoliation. In the following season, the primary leaves also are smaller and fewer in number. Along with this reduction in the number of leaves is a reduction in terminal growth and the dieback of twigs and branches due to starvation and winter injury. Starvation occurs because secondary leaves do not have time to replenish starch reserves, and winter injury occurs because new buds do not have time to harden off before cold winter temperatures arrive. With the death of terminal buds, lateral buds produce clumped foliage the following season. When crown dieback is heavy, epicormic sprouting occurs on the bole and larger branches. Crown vigor can recover from defoliation, but it may take as long as 5 to 10 years.

References: Campbell and Sloan 1977c; Campbell and Valentine 1972; Heichel and Turner 1976, 1984; Staley 1965; Wargo 1981a,b.

As defoliation severity increases, stem growth decreases. Light to complete defoliations resulted in reductions ranging from 4 to 80 percent, reductions of 25 to 70 percent were the most common. In the ring porous oaks, springwood vessels are formed at the time of budbreak from stored food reserves. Complete defoliation may prevent any subsequent summerwood from forming (Fig. 27). Moderate defoliation may result in partial summerwood formation. The variation in growth loss relates to the amount of summerwood formation that occurs since the springwood formation occurs before defoliation. In the year following heavy defoliation, springwood amounts can be reduced due to reduced storage reserves. Because ring porous trees conduct 90 percent of their transpiration water through the current year's springwood vessels, failure to produce springwood will result in death. Several years of springwood formation without summerwood formation will produce wood with reduced specific gravity that is substantially weaker resulting in lower quality products. Recovery of stem growth rates to predefoliation levels generally corresponds to the recovery rate of the crown and may result in loss of 1 to 2 year's increment from an outbreak and reduction in volume growth of 5 to 40 percent over the period.

References: Baker 1941; Brown and others 1979; Campbell and Garlow 1982; Fratzian 1973a,b; Kulman 1971; Magnoler and Cambini 1973; Minott and Guild 1925; Mirkovic and Miscevic 1960; Nichols 1968; Stephens and Waggoner 1980; Turner 1963; Twery 1987; Wargo 1981a; Zimmermann and Brown 1971.

Many small feeder roots die after defoliation, probably from lack of food (Marshall 1986; Staley 1965). This loss of roots results in reduced water and mineral uptake that slows crown recovery (Wargo 1978a). The reduced amount of photosynthate available may reduce the number and longevity of new feeder roots that are formed (Marshall 1986; Marshall and Waring 1985). It also results in a loss of tree vigor, allowing for colonization by secondary insects or pathogens or both. In fact, the recovery of the tree's root system may be the driving force behind tree recovery or death.

Vulnerability to Mortality

The vulnerability of a stand to mortality is defined as its likelihood of suffering mortality following defoliation (Smith 1962). The distinction between susceptibility and vulnerability is important, stands that are highly susceptible to gypsy moth defoliation but have low vulnerability may suffer little mortality when they are subject to frequent heavy defoliation. On the other hand, resistant stands rarely susceptible to defoliation but highly vulnerable may suffer heavy mortality on the unusual occasion when they are defoliated (Bess and others 1947; Houston and Valentine 1977). An understanding of tree responses to defoliation helps to clarify the differences between stand susceptibility and vulnerability. The severity, frequency, and distribution of defoliation, site and stand factors, environmental conditions, invasion by secondary insects and diseases,

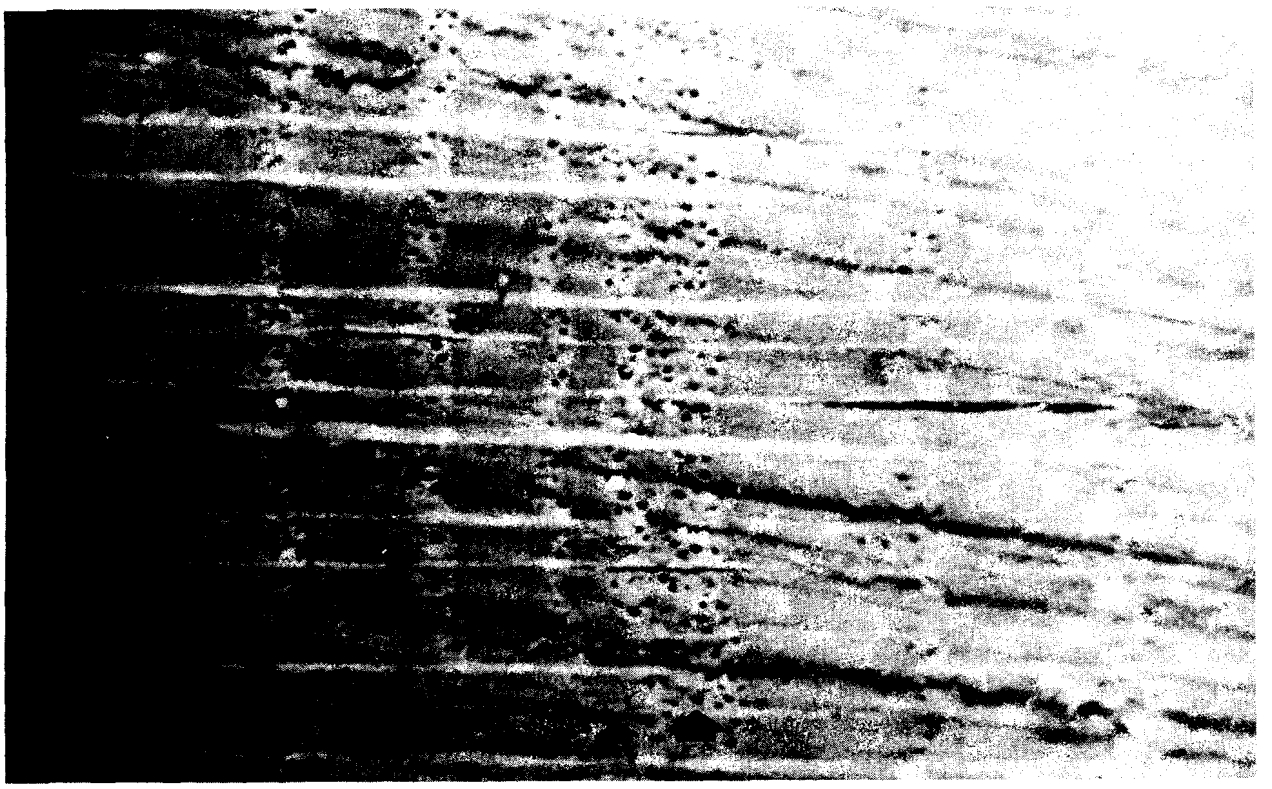


Figure 27.—Influence of gypsy moth defoliation on annual ring growth in nothern red oak from 1978 to 1985 (reading right to left). Defoliation was 100 percent in 1981 (large arrow) and 50 to 60 percent (small arrow) in 1982.

and tree vigor all interact to produce the effects of defoliation (vulnerability) on the tree and stand (Campbell and Valentine 1972; Kulman 1971; Staley 1965; Wargo 1978a,b).

Defoliation

Severity. Gypsy moth defoliation has traditionally been described in three classes: light (less than 30 percent), moderate (30 to 60 percent), and heavy (greater than 60 percent). Light defoliation usually is not noticeable from aerial surveys and causes little or no visible damage to the tree. When a tree is defoliated to the point that it refoliates in the same season, its physiological state is altered significantly (Wargo 1978a). Refoliation occurs in the range of 40 to 75 percent defoliation and results in the mobilization of food (starch) reserves from the roots to produce new leaves and keep the tree alive (Wargo 1978a; Wargo and others 1972). Defoliated trees usually are more vulnerable to other stresses the following season due to these reduced or depleted food reserves. Gypsy moths defoliate trees at the worst possible time—when the leaves are about fully expanded and the tree has maximum energy demands and lowest reserve food levels.

Frequency. Increasing the number of serial defoliations increases vulnerability in most stands, especially resistant ones. One year of heavy defoliation resulted in 7 to 35 percent oak mortality in New England, whereas 2 years resulted in 22 to 55 percent mortality (Campbell 1979; Campbell and Sloan 1977c). Quimby (1982) found the following average mortality percentages for oaks and all species for nine stands in central Pennsylvania: 18 and 17 after one defoliation, 89 and 35 after two defoliations, and 98 and 65 after three defoliations. Campbell and Valentine (1972) noted changes in tree conditions and mortality that occur with successive defoliations. Tree health decreases and crown dieback occurs, eventually leading to mortality (Wargo 1981b).

Distribution. The distribution of defoliation among individual trees is more important for determining vulnerability than stand defoliation levels. Stands that contain high compositions of preferred species could be expected to have uniform defoliation among trees of similar crown class and condition. For these stands, an average stand-level defoliation of 30 percent usually means that approximately 30 percent of the foliage was removed from all of the trees.

All trees would be uniformly subjected to low to moderate stress levels. On the other hand, in stands with mixtures of preferred and nonpreferred species, an average stand-level defoliation of 30 percent may result when preferred trees have 75 to 80 percent defoliation and nonpreferred trees have little or no defoliation (Fig. 28). This situation could result in mortality of preferred species such as oaks with little effect on other species. Campbell and Sloan (1977c) reported exactly this type of pattern as defoliation pressure increased.

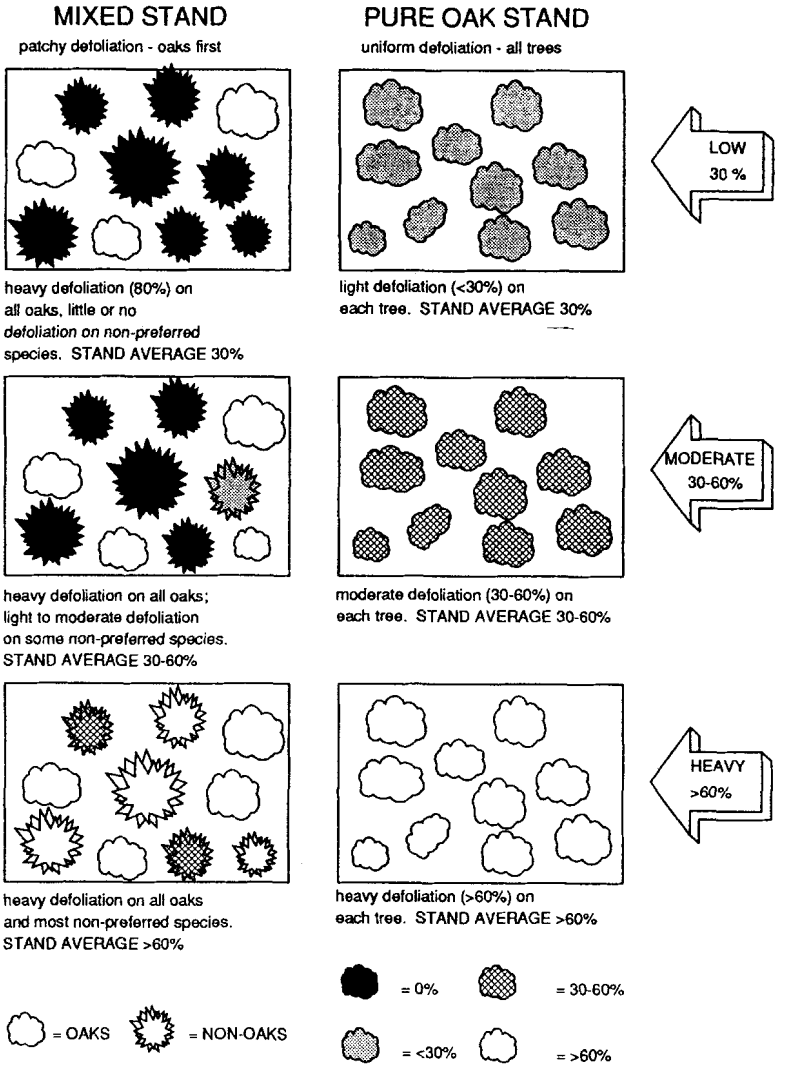


Figure 28.—Progression of defoliation on susceptible and resistant species in stands of varying composition.

Tree Vigor

Tree vigor has been defined as the overall physiological condition or "health" of a tree in a given environment (Wargo 1978a). Physiological condition of the tree must be considered when predicting the effects of defoliation, for it will largely determine the tree's response (Kozlowski 1969). A tree's health has traditionally been measured by general indicators such as crown class and condition for obvious reasons of convenience since a tree's crown is the site of energy conversion required to maintain vitality (Wargo 1978a). Crown class and condition indicate long-term vigor status and may not represent a tree's immediate physiological condition due to stresses that have occurred recently. Relative diameter growth rate also has been used as a general indicator (Trimble 1960); but for various reasons is unreliable. Root starch content and cambial electrical resistance (CER) have been used as short-term indicators of tree health or physiological condition (Wargo 1978c, 1981c). Root starch content, taken at the end of a particular growing season, may represent the cumulative vigor status for one year while CER gives a more-or-less instantaneous measurement of the tree's physiological status.

Crown Condition. Crown condition before defoliation is one of the most important variables that influences mortality. Mortality is highest for poor-crown trees, intermediate for fair-crown trees, and lowest for good-crown trees. However, increasing severity and frequency of defoliation or other stresses can increase the percentage of good crown condition trees that die. Trees have poor crowns when 50 percent or more of the branches are dead; when foliage density, size, and coloration are subnormal; or when epicormic sprouting is heavy. Trees have fair crowns when 25 to 49 percent of the branches are dead; when foliage density, size, and coloration are subnormal; or when some epicormic sprouting is evident. Good-crown trees have healthy foliage, less than 25 percent dead branches, and little or no epicormic sprouting. For further information on rating crown condition of oaks, see Gottschalk and MacFarlane (1992).

References: Campbell 1979; Campbell and Sloan 1977c; Campbell and Valentine 1972; Gottschalk and MacFarlane 1992; Herrick 1982; Herrick and others 1979; Nichols 1968; Wargo 1977.

Crown Class. Crown class and tree size are not as strongly correlated with mortality as crown condition is. As a general rule, defoliated intermediate and suppressed trees are more likely to die than dominant and codominant trees, and either smaller diameter trees or very large, overmature trees are more likely to die than large, vigorous trees. However, as severity and frequency of defoliation increase, more dominant and codominant trees die. The addition of other stresses, such as drought, result in more sawtimber-size trees dying. A dominant tree with a poor crown usually will die before a tree in the intermediate class with a good crown.

References: Brown and others 1979; Campbell and Sloan 1977c; Campbell and Valentine 1972; Crow 1985; Kegg 1971, 1973; Quimby 1985; Statler and Serrao 1983; Stephens 1981.

Physiological Indicators. Two physiological indicators, root starch content and cambial electrical resistance, have been used to compare short-term changes in tree health in the field. Successes in using these indicators have been mixed and their primary use at this time is in research (Wargo 1978c).

Root starch content decreases following defoliation, with the severity and frequency of defoliation affecting the magnitude of the decrease. Utilization of starch reserves for refoliation is the major process that results in the reduction of root starch content. A histochemical technique for visual assessment of root starch content has been developed and can be used in the field without elaborate equipment. Adequate starch levels are needed to support the tree's maintenance respiration over the winter and for springwood formation. Trees with depleted starch levels usually die shortly afterwards, and trees with low levels are also more vulnerable.

References: Wargo 1971, 1972, 1975, 1976, 1978c, 1981a,c; Wargo and others 1972.

Cambial electrical resistance (CER) was first used to measure decayed wood in trees and utility poles, temperature injury, frost hardiness, and diseases in trees. Wargo and Skutt (1975) first examined its potential as an indicator of tree health. They showed that healthy trees had a lower CER than defoliated trees. Cambial electrical resistance has also been correlated with growth rate, foliage biomass, and cambial thickness. Care must be taken in interpreting CER readings because they vary seasonally, with tree moisture status, and from stand to stand. Comparisons must be made on a relative basis within a stand, rather than on an absolute basis. However, CER has shown potential for use in hazard rating of individual trees defoliated by spruce budworm and may also be useful for gypsy moth hazard rating.

References: Blanchard and others 1983; Davis and others 1979, 1980; Fensom 1966; Piene and others 1984a,b; Shortle and others 1977, 1979; Smith and others 1976, 1984; Wargo 1978c, 1981a,c; Wargo and Skutt 1975; Wisniewski and others 1985.

Environmental Conditions

Adverse environmental conditions such as drought, late spring frosts, and excessive moisture can cause additional stress on trees before, during, and after defoliation resulting in higher mortality from the combination of stresses than that from any single condition. Temperature and moisture conditions during the defoliation and refoliation periods affect the amount of defoliation, development of leaf diseases, the production and expansion of refoliated leaves, overall tree vigor, and development of secondary organisms.

References: Heichel and others 1972; Karnig and Lyford 1968; Law and Gott 1987; Nichols 1968; Quimby 1985; Staley 1965; Stringer and others 1989; Wargo 1978a, 1981b.

Site and Stand Factors

It is difficult to generalize about site and stand factors because mortality can be found in almost every situation. However, a few observations can be made. Though gypsy moth defoliation is most severe on poorer sites, when defoliation occurs on moister, mesic sites with higher site indices, mortality tends to be higher. This does not mean that heavy mortality cannot be found on poor sites. Elevation, aspect, percentage of rock, site index, slope position, slope percent, mean d.b.h., total basal area, and other variables occasionally have been correlated with mortality.

Mortality usually is highest among preferred food species, possibly reflecting greater defoliation levels, though some resistant species can be greatly affected. General mortality figures range from 5 to 80 percent, most commonly between 5 and 50 percent, while specific mortality of oaks ranges from 5 to 100 percent, most commonly 10 to 60 percent.

Data in the following references represent a variety of physiographic areas, sites, stand compositions, stand conditions, and defoliation intensities and frequencies. Therefore, it is not surprising that gypsy moth-related mortality seems unpredictable, confusing, and contradictory. **A rule-of-thumb is that managers can expect 15- to 35-percent average mortality the first time gypsy moth defoliates an area. Some stands will have less and some with have more—up to 60 to 80 percent or higher in stands where drought or other stresses are present simultaneously with defoliation.** Because of the mortality that has occurred, subsequent defoliation periods may result in less mortality than the initial period.

References: Atkins and Smallwood 1991; Baker 1941; Brown and others 1979, 1988; Campbell and Garlo 1982; Campbell and Sloan 1977c; Campbell and Valentine 1972; Crow 1985; Crow and Hicks 1990; Dunbar and Stephens 1975; Fosbroke and Hicks 1989; Fosbroke and others 1991; Gansner 1981, 1987; Gansner and Herrick 1979, 1982, 1984a, 1987b; Herrick and Gansner 1987b, 1988; Herrick and others 1979; Hicks 1984; Hicks and Fosbroke 1987; Houston and Valentine 1977; Kegg 1971, 1973, 1974; Minott and Guild 1925; Montgomery and others 1989; Perry 1955; Quimby 1982, 1985, 1987; Statler and Serrao 1983; Stephens 1971, 1981, 1984, 1987, 1988; Stephens and Hill 1971; Stephens and Ward 1992; Tigner 1992; Turner 1963; Widmann and others 1992.

Secondary Organisms

Defoliation by the gypsy moth rarely kills hardwood trees directly. Nearly all trees that die following defoliation by gypsy moth are attacked by secondary or "opportunistic" organisms such as shoestring root rot, a fungus that attacks the roots, and the twolined chestnut borer, an insect that attacks the phloem and cambium layers. Healthy trees can resist or tolerate attacks from these organisms. When both organisms are excluded; trees can tolerate several years of defoliation and still survive. In many instances, both organisms attack defoliated trees, though either one alone is sufficient to cause death.

References: Baker 1941; Cote and Allen 1980; Dunbar and Stephens 1975; Houston 1981a,b; Nichols 1968; Staley 1965; Wargo 1977, 1978a; Wargo and Montgomery 1983.

Shoestring Root Rot. Armillaria spp. or the honey fungus has been the subject of much research. When a tree has been weakened and its root starch levels lowered, along with other chemical changes, the fungus successfully attacks the weakened and dead roots. The fungus enters the root system and mycelia progress throughout the tree's root system destroying the inner bark and wood. Death occurs when the entire base of the tree is girdled, and in some instances, the mycelial fan can extend up the stem 10 to 15 feet or more. Chemical changes that occur in the stressed root system seem to predispose the tree to *Armillaria*. There is a potential for developing treatments to protect trees from shoestring root rot, but they may not be practical for widespread field use.

One possible explanation for the increased mortality of oaks on better sites and in disturbed stands is the occurrence of larger populations of *Armillaria* in moist soils and areas with abundant food sources (disturbed and thinned stands). In particular, the interaction between forest management actions and *Armillaria* population levels may prove to be extremely important for future management. Surveys of the distribution of *Armillaria* in forest stands are needed to confirm this relationship.

References: Houston 1981a,b; Long 1914; Mallett and Hiratusuka 1985; Pawsey and Rahman 1976; Shaw and Kile 1991; Twery and others 1990; Wargo 1980, 1981d, 1984a,b; Wargo and Houston 1974; Wargo and Shaw 1985; Wargo and others 1972, 1987.

Twolined Chestnut Borer. This insect is attracted to and attacks weakened trees. Investigators found that as root starch levels decreased, the number of successful attacks by twolined chestnut borers increased. The larvae of the borer feed in the cambium and phloem layers starting in the branches and working down to the stems of oaks and chestnut, eventually girdling them. The larval development period is from June through September. The last two instars (August and September) are the most destructive, resulting in characteristic "burned-out" branches that have prematurely wilted, with brown foliage remaining attached. These trees die in 1 to 3 years. Dunn and others (1986a,b) have found that volatile chemicals released from stressed oaks attract adult females to the tree, where they then lay their eggs. Adults prefer to eat oak foliage, also ensuring that females will be close to potential larval hosts.

Although not commonly practiced, there are options for reducing populations and damage by the twolined chestnut borer. Several sanitation treatments are possible. Infested trees can be cut down between the end of the egg-laying period (late June) and mid-July. The larvae will not survive the drying of the cambium at that stage, however, felling later than mid-July resulted in successively higher survival rates. Another sanitation measure is to remove low-vigor or unhealthy trees and maintain or increase overall stand vigor. Trap trees also can be effective in reducing borer populations within a general locale. Oaks are girdled as close to the ground as possible in May or June. The girdled trees emit volatile chemicals that attract females who lay their eggs in the trees. Larvae hatch and begin normal development; but most will eventually die from desiccation as the tree dies. The same effect can be observed in slash or logs from thinnings during the same time period.

More direct control can be obtained by spraying the bark of infested trees with an insecticide during May. The adults are killed in their pupal chambers or from ingesting the insecticide as they emerge from the bark. The adults also can be killed from foliar applications of insecticides during June and July. None of these control methods will save trees that are already infested, but they will help prevent spread to uninfested trees in the stand. Another control treatment would be the use of mass-produced oak volatile attractants in sticky traps that would attract and mass trap adults, but this approach depends on the successful isolation and identification of the attractant(s).

References: Dunbar and Stephens 1974, 1975, 1976; Dunn and others 1986a,b, 1987, 1990; Haack 1985; Haack and Benjamin 1980a,b, 1982; Wargo 1977; Wargo and Montgomery 1983.

Long-Term Ecological Impacts

Present Stands

Data from several New England studies suggest that long-term changes in present stands consist of a reduction in oaks and other preferred species, an increase in non-preferred species, and a reduction in subdominant trees. These changes are very similar to natural successional processes in New England, so defoliation by the gypsy moth has hastened succession. These changes also have reduced the susceptibility of the stands to future defoliations due to the shift in species composition to less preferred species. The exception is higher elevation chestnut oak stands that are already stable sub-climax communities. Heavy mortality in these stands may return the area to an earlier successional stage—shrubs or herbs. Long-term stability between the gypsy moth and forest may develop due to: 1) an increase in the abundance of nonpreferred species; and 2) selection for more hardy individuals of the preferred species. These changes would result in forests where gypsy moth outbreaks occur less frequently, have a shorter duration, and result in less mortality (reduced susceptibility and vulnerability).

References: Campbell 1979, 1981; Campbell and Sloan 1977c; Stephens and Ward 1992.

Plots were monitored in northeastern Pennsylvania's Pocono Mountains for an 8-year period and central Pennsylvania for a 7-year period (Gansner and Birch 1989; Gansner and others 1983). They found a reduction in oak basal area, fewer trees per acre, little change in average basal area, and a reduction in the number of overstocked stands. However, a few stands had very heavy mortality losses. McCay and White (1973) projected that sawtimber stands would drop slightly in stocking while pulpwood stands would remain adequately stocked. Quimby (1985) and Donley and Feicht (1985) analyzed a large area in central Pennsylvania, and reported drastic stocking reductions in some specific stands due to drought and previous management practices, but Gansner and Birch (1989) showed only minor reductions in stocking.

Future Stands

The impact of gypsy moth on regeneration is usually much more subtle. Even without gypsy moth defoliation, oak regeneration has been difficult to obtain in many areas, but with it, regeneration becomes even more difficult. Dead oak stems lack the capacity for sprouting and stump sprouts are often the only reliable form of oak regeneration in cutover oak stands. Defoliation also reduces the production of acorns resulting in a reduction in the number of advanced regeneration seedlings present. Finally, defoliation increased growth and decreased natural mortality of other competing, nonpreferred understory plants. These responses work against oak regeneration and favor more

tolerant species with the exception of poor sites where oak is the stable sub-climax and was successfully regenerating itself. For example, in central Pennsylvania, stands that were dominated by oak before gypsy moth, now contain regeneration dominated by red maple and black birch. **The long-term trend in future stands is away from oaks and other preferred species toward non-preferred climax associations.**

References: Allen and Bowersox 1989; Collins 1961; Crawley 1985; Ehrenfeld 1979, 1980; Gansner 1985; Gottschalk 1982, 1983, 1988, 1990b; Langhoffer 1929; McConnell 1988; Stephens and Waggoner 1980; Stephens and Ward 1992.

CONCLUSIONS

Although these guidelines have not been extensively tested, a number of studies are underway to test them and results of other studies have contributed to their development and revision. The guidelines represent the current knowledge of the impacts of gypsy moth defoliation on forest stands. Opportunities exist to manage forests in areas where the gypsy moth is or will be present in an economical manner without sacrificing management objectives or allowing the insect to dominate management actions as has happened in many areas of Pennsylvania, New York, and other infested areas. Eventually the forest, forest managers, and this exotic insect pest may approach a state of tolerable coexistence.

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Gottschalk, Kurt W. 1993. **Silvicultural guidelines for forest stands threatened by the gypsy moth.** Gen. Tech. Rep. NE-171. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 49 p.

Ecological and silvicultural information on the interaction of gypsy moth and its host forest types is incorporated into silvicultural guidelines for minimizing the impacts of gypsy moth on forest stands threatened by the insect. Decision charts are used to match stand and insect conditions to the proper prescription that includes instructions for implementing it.

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Keywords: oak-hickory forest type, integrated pest management, forest management, silvicultural systems, *Lymantria dispar* (L.), intermediate stand treatments, regeneration treatments, salvage cutting.

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