United States Department of Agriculture

Forest Service

Northeastern Forest Experiment Station

General Technical Report NE-91

1985

# Green Woods Model: A Forecasting Tool for Planning Timber Harvesting and Protection of Spruce-Fir Forests Attacked by the Spruce Budworm

Robert S. Seymour
D. Gordon Mott
Steven M. Kleinschmidt
Peter H. Triandafillou
Robert Keane

## The Authors

Robert S. Seymour is assistant research professor with the College of Forest Resources, University of Maine, Orono. He received a B.S. degree in forest management from Ohio State University, and M.F. and Ph.D. degrees from the Yale School of Forestry and Environmental Studies.

D. Gordon Mott, retired research forester with the Northeastern Forest Experiment Station, received a B.S. degree in forestry from the University of New Brunswick and an M.F. degree from the Yale School of Forestry. Currently he is a consulting forester in Newburgh, Maine.

Steven M. Kleinschmidt is a resource analyst with Champion International Corp., Missoula, Montana. He received a B.S. degree from Iowa State University and a M.F. from the Colorado State University.

Peter Triandafillou is a forester and program specialist with James W. Sewall Co., Old Town, Maine. He received a B.S. degree in biology from Columbia College and an M.S. degree in forestry from SUNY College of Environmental Science and Forestry, Syracuse.

Robert Keane is a graduate student in forest management at the University of Montana. He received a B.S. degree in forest engineering from the University of Maine.

Manuscript received for publication
8 December 1983

## Abstract

A dynamic model of budworm-infested spruce-fir forests is described. The Green Woods Model allows managers and analysts to predict forest composition and structure that result from various harvesting and protection strategies. The forest structure is represented as a distribution of area and volume by age class, species, and forest type. This structure changes through time as the natural process of forest development (growth, budworm-caused growth loss and tree mortality, and regeneration) interact with management strategies (timber harvesting and protection). The model is inherently flexible; the rate and timing of virtually all modeled processes, both natural and management-related, are controlled by the user. Included is an example of how the model can be applied with conventional forest-inventory data. The main simulation program is coded in PL-1; auxiliary software in WATFIV is available to assist users in constructing input data and summarizing results.

# Contents

# Introduction

When the current spruce budworm (*Choristoneura fumiferana* Clem.) outbreak became severe during the mid-1970's, managers and policymakers were faced with a difficult decision: How much of Maine's spruce-fir resource should be protected against tree mortality to sustain the present industry? Initially, a conservative stance was taken, and all infested areas were sprayed where the hazard warranted. However, the situation developed rapidly and by the late 1970's the need for change in Maine's budworm suppression policy was evident. Powerful forces, including environmentalists opposed to large-scale insecticide applications and landowners dissatisfied with the inequitable distribution of budworm spray costs, were at work to limit the size of Maine's protection program. Legislation was passed that changed dramatically the way in which Maine's spray program is funded. The switch from the "fire-control insurance policy" model to the "pay-as-you-spray" approach (Rumpf et al. 1982) forced landowners to limit protection to only those stands where spraying clearly was justified.

At the same time, the Green Woods Project was formed at the University of Maine's School of Forest Resources through funding provided by the Canada-United States Spruce Budworms Program (CANUSA). Green Woods was a joint effort between spruce-fir forest managers and scientists to develop and apply an integrated protection-management system that would reduce protection costs and maintain spruce-fir wood supplies. Major cooperators in this project were Great Northern Paper Co., Seven Islands Land Co., and the Baxter Park Authority. Collectively, these cooperators manage more than 3 million acres in Maine. The operational aspects of the program centered around harvesting and spraying treatments that were "targeted" on the basis of the balsam fir component of stands (Dimond et al. 1984).

Field application of the program on three demonstration areas was relatively straightforward. However, soon after the project's inception it was evident that a major component of the system was missing. There was no analytical capability for forecasting the long-term outcome of targeted treatments. As a result, it was not possible to predict whether certain intuitively reasonable harvesting or protection strategies would reach their stated goals.

To address this need, the Green Woods simulation model was developed. The model was designed to:

1. Capture the general structure and principal dynamics of budworm-infested red spruce (*Picea rubens*)-balsam fir (*Abies balsamea*) forests.

2. Allow forest managers to predict, through simulation, the consequences of a wide array of combined harvesting-protection strategies.

3. Stimulate additional research into particular aspects of spruce-fir forest development, with the aim of improving the manager's predictive capability.

Since its creation in early 1980, the model has been used widely in Maine. After its initial application[1], several major landowners followed with analyses of their ownerships, which encompass more than two-thirds of Maine's spruce-fir resource. More recently, the model was used to analyze the supply and demand of spruce-fir for the State of Maine (Sewall Co. 1983).

In the course of these applications, the model has undergone substantial revision. Its technical structure has been modified on the basis of recent analytical developments, and auxiliary software has been added to make it much easier to use by those who have had little or no experience with computers. The intent of this paper is to describe the model and to facilitate its distribution to and application by a much wider audience. The first section describes the model structure and illustrates how it works; the second shows how it can be applied to a typical management problem. Specific functions, sample worksheets for summarizing input data, and programming considerations are included in the Appendix.

[1] Seymour, R. S.; Mott, D. G.; Kleinschmidt, S. M. Future impacts of spruce budworm management—a dynamic simulation of the Maine forest 1980-2020. Unpublished report of the Green Woods Project; 1980. 88 p. On file at the University of Maine, College of Forest Resources, Orono.

## Model Description

### General Organization

The Green Woods Model is a general predictive tool that allows a manager to forecast the development of a spruce-fir forest in response to natural processes and management inputs. The forest structure is represented as a distribution of area by forest type, age class, and species. The model grows, kills, harvests, regenerates, and protects the simulated forest, and generates annual descriptions of its condition, including inventory, growth rate, recent mortality, age structure, species composition, and many other useful attributes (Fig. 1). Because the rate and timing of all processes are set by the user, the model is inherently flexible in its ability to replicate special situations.

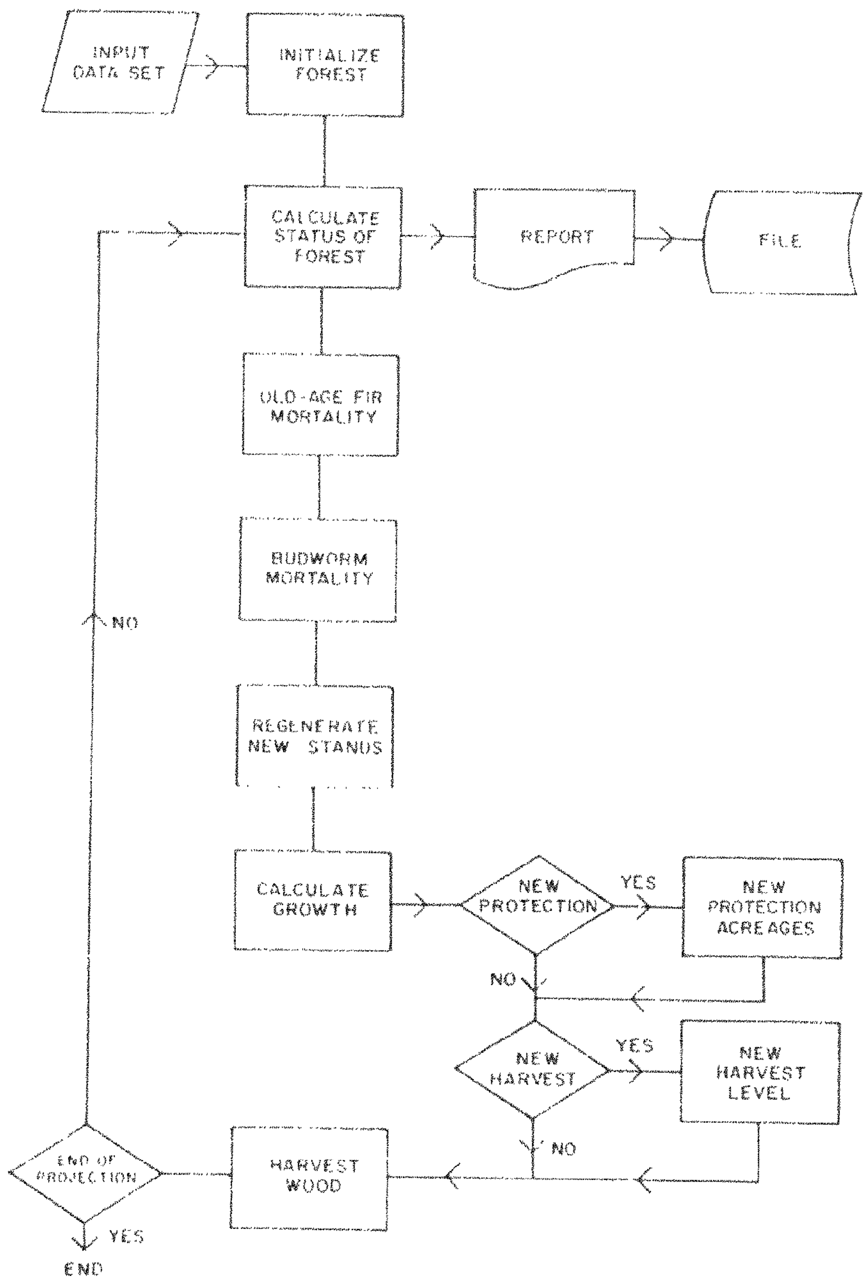


Figure 1. Flow chart of the Green Woods Model

## Forest Structure

The Green Woods Model represents the spruce-fir forest by distributing its total area into the categories shown in Figure 2. Only the spruce-fir component of the forest is simulated. Forest types (e.g., hardwood) with little volume of budworm host species are excluded from the resource.

Attributes of this forest area—primarily species composition, stocking, and age structure—are defined by the user. During a simulation, forest structure changes as growth, mortality, regeneration, budworm attack, timber harvesting, and forest protection alter the areas and volumes in each category.

### Protected and Unprotected Lands

The first major division of forest area is between lands that are either protected or unprotected against budworm attack. Protected lands are defined as the portion of the forest with no tree mortality during a simulated outbreak. They are intended to represent the total area where a successful forest protection program (usually aerial spraying of insecticides) is applied as needed to keep trees from dying. Partitioning the simulated forest structure on this basis is a crucially important feature of the model. In addition to mortality, other modeled processes (growth reduction, regeneration, harvest allocation) also are controlled by protection status to a significant extent.

Users specify the characteristics of the protected lands and can simulate targeted programs. Through changes in protection strategies, the area under protection can be reduced or, in certain cases, increased by shifting lands between categories. This has the effect of changing the total area on which there is tree mortality and reduced growth. If no outbreak is underway, the model treats all lands as if they are "protected" (no budworm-caused tree mortality), even though no protection program is applied.

### Forest Types

The next major division of land is between softwood and mixedwood forest types, which are defined on the basis of the relative stocking of hardwood (nonhost) species. In Maine, stands with more than three-fourths of the total stand volume in coniferous species are classified as "softwood." Species composition usually is some mixture of spruce and fir, though some stands dominated by northern white cedar (*Thuja occidentalis*) also are included in this type. In mixedwood stands, the softwood component usually ranges from one-fourth to three-fourths of total stocking. Stands with less than 25 percent of the volume in softwood are typed as hardwood stands and are not a part of the resource simulated by the model.

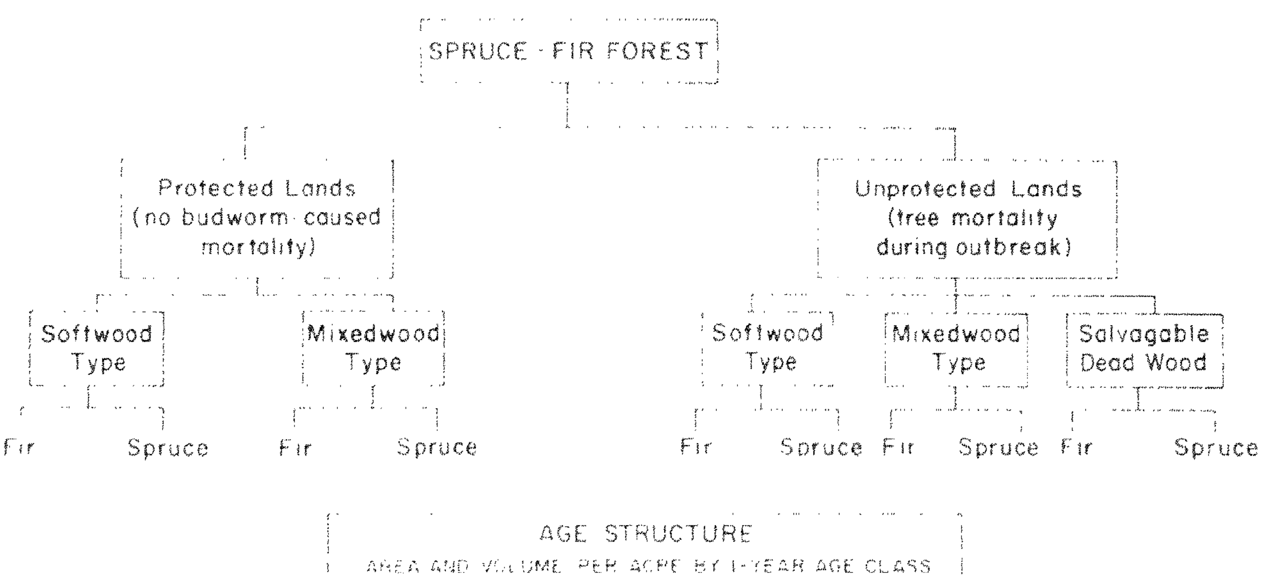


Figure 2.—General structure of a spruce-fir forest as represented by the Green Woods Model.

Though the exact definitions may be somewhat arbitrary, the distinction between softwood and mixedwood types is valuable for modeling purposes. Softwood and mixedwood stands differ in site quality, growth rate, vulnerability to budworm damage, and ease of regeneration, and usually are managed differently as a result. Separating softwood and mixedwood areas in the model allows the forest dynamics to be modeled more accurately. Also, because these types are readily distinguished on aerial photos, maps prepared on this basis generally are available for most large landholdings in the spruce-fir region, and forest inventories usually have been stratified on a forest-type basis. Thus, the basic resource data needed to run a simulation already are available to most managers of spruce-fir forests.

**Age Structure**

The next major division of the forest, and the key to the way it simulates forest dynamics, is the distribution of area by age class. All processes affecting forest development and management are modeled on the basis of age. Rates of growth and vulnerability to budworm damage are specified as functions of age; the major management practices—harvesting and budworm protection—are allocated to particular age classes; and forest regeneration is modeled by removing area from older age classes after harvesting or mortality and adding it back to young age classes the following year.

Because some (Westveld 1953) have recommended silvicultural systems based on an uneven-age model of stand development, the choice of an even-age paradigm for modeling spruce-fir forest dynamics merits further discussion. Overwhelming historical evidence (Mott 1980) and studies of stand development (Baskerville 1965, 1975; Mott 1976; Seymour 1980) indicate that the current spruce-fir forest originated from heavy disturbances that operated on a scale much larger than individual trees within stands. Logging of the virgin red spruce from 1870 through the 1920's, the intense spruce budworm outbreak of 1912-20, and periodic destructive windstorms and bark beetle outbreaks removed the mature forest over large areas essentially at once. Stands that regenerated afterward have developed in distinct phases characteristic of even-aged forests: an early period when trees gradually occupy the site; a period during midlife when height growth accelerates and merchantable volume accumulates rapidly as trees cross the ingrowth threshold; a period during maturity when height growth slows, no new recruitment occurs, and volume growth is limited to accretion in diameter; and finally, if no harvesting or budworm attack occurs, a period of overmaturity when natural mortality may exceed accretion and net growth becomes negative. Although widespread application of partial cutting has obscured this pattern in some cases, a concensus clearly has emerged that the present spruce-fir forest is more naturally even-aged than otherwise.

As used in the Green Woods model, age classes are actually stages in stand development. Exact biological age is not crucial. Once a simulation is underway, "ages" of the various strata are really indexes of the time elapsed since the beginning of the run. Similarly, for stands regenerated during a simulation, "age" is an index of time elapsed since harvesting or budworm-caused mortality.

**Species Composition**

The final major division of forest land is between the two major hosts of the budworm—balsam fir and spruce. The spruce component in Maine, for which the model was developed originally, is primarily red spruce, but other spruce species could be used. There are important differences between balsam fir and spruce in growth, longevity, regeneration, and vulnerability to budworm damage. Maintaining separate areas for spruce and fir in the model allows the user to vary these processes in accordance with local experience or published information.

In the model, the total area in each age class is allocated to spruce or fir in proportion to the relative stocking of each species. In terms of simulating forest dynamics, these "model areas" are treated as pure "stands" of spruce or fir, even though no actual stands are recognized. The model grows, kills, and regenerates spruce or fir areas on the basis of age and forest type only. The relative species composition of the affected age class is not a controlling factor.

Conceptually, these spruce or fir "model" areas represent areas in the real forest occupied by spruce or fir trees. Areas defined in this manner are artificial only in the sense that they cannot be tied directly to a stand type map. Thus, the difference between "real" and "model" areas is simply a matter of scale. Because the model does not attempt to simulate individual stands, this is not a serious deficiency. The purpose of this model is to replicate spruce-fir dynamics and management practices on a forestwide basis. This simple structure eliminates the need to keep track of areas in particular species mixtures, with little loss in realism in simulating natural forest-level dynamics.

The primary situations where the true, mixed composition of spruce-fir stands must be recognized explicitly are in the application of management activities—timber harvesting and budworm protection—which are applied to "real" acres. In both of these instances, mechanisms are provided for generating realistic proportions of spruce and fir in the volumes harvested and acres protected.

Stocking

Once its *area* structure is defined, the forest is stocked with merchantable cubic volume. In general, this is done by supplying the model with the average volumes per acre by age class for each of the four major divisions of forest area (one each for fir and spruce in both the softwood and mixedwood types). Total forest volumes are obtained by multiplying areas by volume per acre for each species and age class, then summing over all age classes.

**Algorithms Used to Define Initial Forest Structure**

To define the forest structure, the total area in both the softwood and mixedwood type is distributed into age classes. Although 1-year classes are maintained internally, data are input by 10-year classes for convenience. Up to 15 classes can be specified, with the oldest area in the 141-150 age class. Softwood and mixedwood types can have separate age-class distributions.

After the area is distributed by type and age class, two options are available for defining the initial stocking levels and the proportions of spruce and fir in the forest. Volumes per acre can be input as a percentage of Meyer's (1929) normal yield tables or directly as per-acre volumes by species, depending on the nature of the data available to the user.

*Percent-of-normal stocking option.*—Under the Meyer percent-of-normal stocking option, stocking for each 10-year age class is specified as a proportion of the merchantable volumes given in Meyer's (1929) normal yield tables. Stocking percentages are given separately for each forest type by 10-year age class. A Weibull distribution function fitted by nonlinear regression to Meyer's data for Site Index 50 (softwood type) and Site Index 60 (mixedwood type) is used (Appendix I). Figure 3 shows the volumes per acre obtained when 50 percent stocking is used for all age classes in the softwood type and 30 percent is used for mixedwood.

After total stocking is defined, areas and volumes are allocated to individual species. Separate arrays used for both the softwood and mixedwood types correspond to those used for the age-class distribution and stocking. The user specifies the percentage of each 10-year age class that is occupied by fir. This should be done on the basis of how much area actually is occupied by each species, regardless of whether they are in pure or mixed stands. Obviously, measuring these areas directly on an individual-tree basis is not feasible, so an alternative approach is used.

According to Meyer (1929), volumes of fully stocked "normal" stands of pure red spruce and pure balsam fir are quite similar at the same age. This suggests that spruce and fir are close substitutes for each other in terms of growth and yield. Thus, over an entire forest, the volumes of fir and spruce that accumulate in a given age class should bear a direct relationship to the areas actually occupied by each species. For age classes with merchantable volume (those over 25), the relative volumes by species are used to apportion areas.

Age classes under 25 have no volume in the model, so areas must be assigned directly on the basis of the expected proportion of fir and spruce when the young areas reach merchantable size. These data should be consistent with the

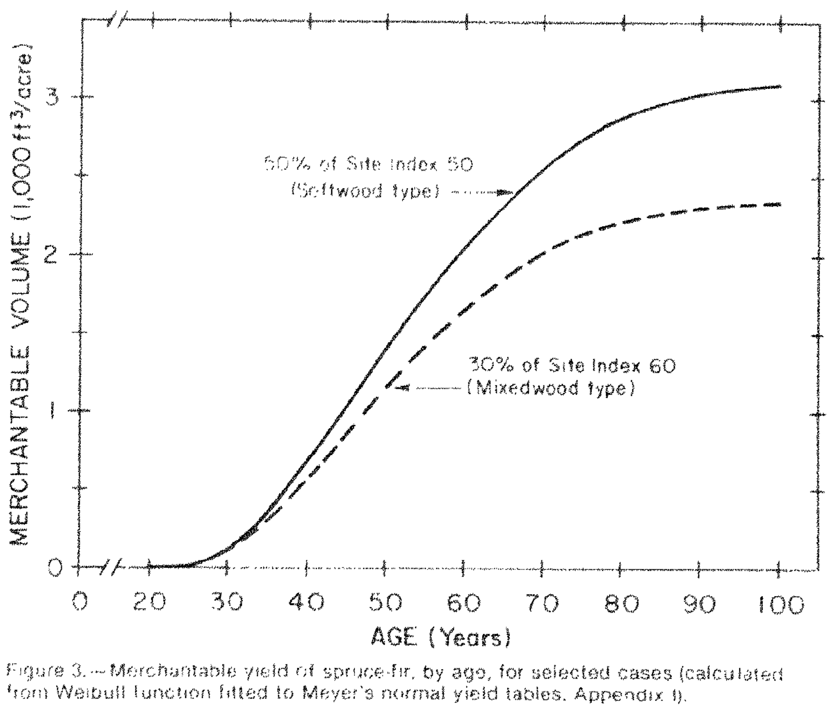


Figure 3.—Merchantable yield of spruce-fir, by age, for selected cases (calculated from Weibull function fitted to Meyer's normal yield tables, Appendix I).

assumptions used to determine the species composition of the regeneration, but are not necessarily the same as the stocking on regeneration plots taken immediately after logging. Stand composition may change by the time trees reach merchantable size, either due to differences in natural development or because early density-control treatments were applied to favor one species. Unlike the real world, species composition in the model is fixed until the areas are old enough to be affected by harvesting or budworm mortality. Therefore, compostion of the unmerchantable age classes must reflect the end result (at age 25) of these early stand dynamics, not the initial condition.

*User-supplied stocking option.*—If inventory data are available with volumes of spruce and fir by age class, these can be specified directly by the user, eliminating the need to determine normal-stocking and fir percentages. When this option is selected, users input the actual volumes per acre by species and 10-year age class for both forest types. The program then automatically calculates the proportions of spruce and fir, and distributes the area within each age class accordingly.

Volumes per acre of a particular species taken from inventory data apply to the entire area in the age class ("real" areas), not just to the area actually occupied by that species and no others (represented by the pure-species "model" areas). Thus, spruce and fir stocking levels obtained from inventory data are converted by the model to hypothetical pure-stand stocking.

Actual volumes per acre are multiplied by the factor TA/SA, where TA equals to the total area in the age class and SA equals the area allocated to the particular species (fir or spruce). In effect, there is higher stocking on fewer acres, but the same total volume results over the entire area in the age class. Since age classes below 25 have no volume, those must be allocated explicitly as in the normal-stocking option.

Because these pure-species model areas (the SA's) are determined by the relative volumes per unit area, calculated stockings of spruce and fir *expressed on a model-acre basis* are equal with this procedure. Thus, different total volumes in an age class result entirely from having different total areas occupied by each species. These assumptions initially may confuse users who select this option to stock their simulated forest, but it is simply the logical outcome of the fact that spruce and fir essentially are equally efficient in growth per unit area.

Examples presented in the section on applying the model show these processes in detail. The following example compares the normal-yield function and user-supplied stocking algorithms for defining initial forest structure:

*Both Options*

*User provides:*

1. Total type area = 1,000 acres
2. Proportion of area in 51- to 60-year-old stands = 0.10

*Model calculates:*

1. Area in 51- to 60-year-old stands = 0.10 × 1,000 = 100 acres
2. Area in each one-year class = 0.1 × 100 = 10 acres

*Normal Yield Function Option*

*User provides (for each 10-year age class):*

1. Proportion of normal stocking = 0.50
2. Proportion of age class in fir = 0.40

*Model calculates:*

1. Volume per acre = 0.50 × 2,919 (Age 51, from Appendix I) = 1,460 $ft^3$ per acre
2. Area in fir = 0.40 × 10 = 4 acres
3. Area in spruce = 10 − 4 = 6 acres

(Note: Each 1-year, internal age class has a different stocking under this option.)

*User-Supplied Stocking Option*

*User provides (for each 10-year age class):*

1. Fir volume per acre = 584 $ft^3$
2. Spruce volume per acre = 876 $ft^3$

*Model calculates:*

1. Total volume per acre = 584 + 876 = 1,460 $ft^3$
2. Proportion of fir = 584/1,460 = 0.4
3. Area in fir = 0.4 × 10 = 4 acres
4. Area in spruce = 10 − 4 = 6 acres
5. Volume of fir on *model* "fir acres" only = $\frac{584 \times 10}{4}$ = 1,460 $ft^3$
6. Volume of spruce on *model* "spruce acres" only = $\frac{876 \times 10}{6}$ = 1,460 $ft^3$

(Note: All 1-year, internal age classes within the 10-year class have the same stocking under this option.)

## Natural Processes of Forest Development

### Forest Growth

The rate at which the simulated forest grows is determined by age, species, and forest type, and may be reduced for the effects of budworm defoliation differentially on protected and unprotected lands. Growth rates can be specified directly on a per-acre basis by species and age class, or can be calculated from an optional mathematical function. The function currently programmed is a Weibull formulation of Meyer's (1929) normal yield tables, but any function can be accommodated. Additional flexibility is provided by user-controlled adjustment factors specific to each species and forest type, which raise or lower growth rates proportionally over all age classes. In this manner, the user can specify both the *shape* and *level* of the growth function, which facilitates the process of calibrating the forest to reproduce historical patterns. Another possible use would be to predict the results of management practices designed to increase growth rates on particular components of the forest.

Use of a *growth* function to simulate forest development allows the major influences to be applied annually, in any combination, and at rates which can vary over time. The forest can "react" dynamically to each; the resulting structure is the logical accumulation of these perturbations. For predicting and analyzing budworm impact, this is a major advantage over models based on yield-table projections. The latter fix stand development for an entire rotation in advance, and can be too rigid to simulate these processes unless "defoliated" strata are redefined during a simulation.

Growth rates used as model inputs are modified *net* growth rates. They are intended to represent ingrowth plus accretion minus normal (noncatastrophic) mortality only. Budworm-caused tree mortality is calculated and applied separately. The net growth of the entire forest computed by the model is a true net growth, including the effect of budworm-caused mortality, if any.

In the model, forest growth is the result of two distinct, independent processes which occur annually during a simulation. First, the forest is "aged" by advancing the age-class distribution (which is maintained internally by 1-year classes) by 1 year. Areas removed from older age classes by harvesting or budworm mortality are added back to the first age class to simulate regeneration. Second, stocking levels are updated annually by adding the net annual growth to the year-end volume per acre of the previous (1-year younger) age class. For a particular age class, the product of these two variables—area times volume per unit area—gives the total volume in that class. "Growth" is the difference between the new and previous total volumes, summed over all age classes for each type, before harvesting and budworm mortality take place.

*Growth function option.*—Nonlinear regression was used to fit a Weibull distribution function to Meyer's (1929) normal yield table (Appendix I) for Site Index 50 (used for the softwood type) and Site Index 60 (mixedwood type). Site index from Meyer's tables is the height of condominant spruce at a total age of 65. Because the model requires annual growth, not yield, the equivalent Weibull density function (i.e., the derivative of the distribution function, with the same parameters) is solved repeatedly to obtain growth rates for each age class.

Meyer's tables predict growth for fully stocked "normal" stands, and usually must be reduced to match observed growth on large areas that are less well stocked. Four user-supplied calibration factors, one each for fir and spruce in both the softwood and mixedwood types, reduce or increase the level of the growth function proportionately over all age classes. Figure 4 shows the growth rates predicted

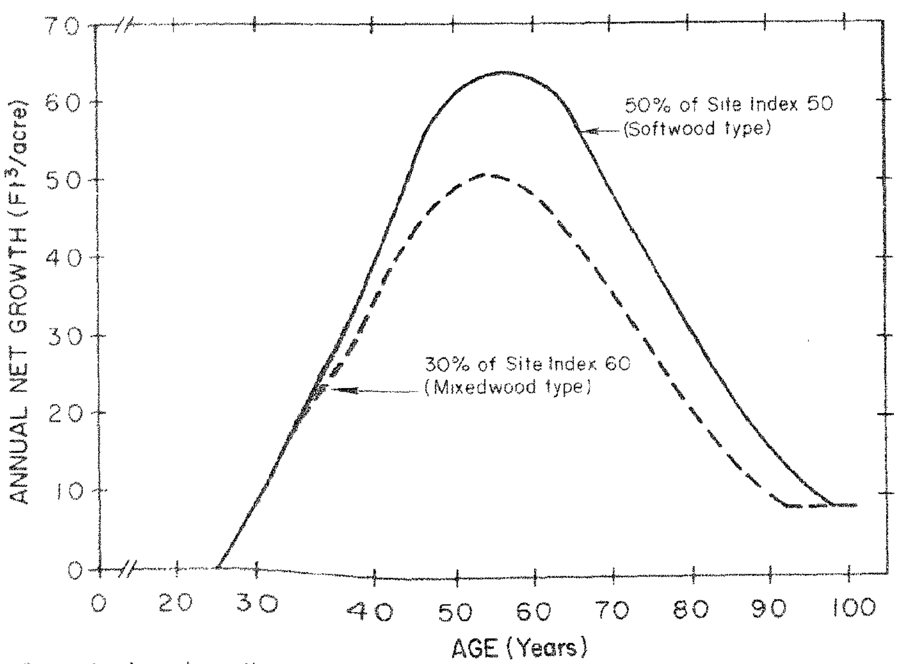


Figure 4.—Annual growth of spruce-fir, by age, for selected cases (calculated from Weibull density function fitted to Meyer's normal yield tables, Appendix I). Rates do not include allowances for mortality caused by the budworm or old-age, which are applied separately.

using 50 percent of Meyer's values in the softwood type and 30 percent in the mixedwood type.

Growth rates from the unmodified growth function for normal stands approach zero as full site occupancy is reached at older ages. This probably is not realistic for stands of below normal stocking, so simulated growth in older age classes is not allowed to fall below 8.5 ft³ (0.1 cord) per acre per year. Calibration factors modify this rate by species and forest type, as described previously.

*Old-age fir mortality.*—Meyer's tables show that yields of red spruce and fir are similar, so the same function is used to compute growth for both species. However, yield tables for the Lake States (Gevorkiantz and Olsen 1950) and studies of old-growth fir stands in New Brunswick (Baskerville 1965) show that stands of fir begin to break up from natural causes beyond age 70. Seegrist and Arner (1982) also present conclusive evidence that fir has a much higher probability of dying from natural causes than spruce, especially in the larger diameter classes. Most mature firs are severely weakened by heart rot and tend to break off or uproot in windstorms, resulting in mortality which exceeds accretion. To simulate this process, an "old-age" mortality function (Fig. 5, Appendix I) can be applied annually (at the user's option) to "kill" varying proportions of the fir volume over age 50.

Meyer's tables are gross volumes (inside bark) for all trees in and above the 4-inch d.b.h. class. In Maine, merchantable volumes are more typically calculated only for 5-inch and larger trees, including bark, and may have deductions for cull applied differentially by species. As a result, Meyer's functions may predict growth rates that are too high in young age classes dominated by 4-inch trees, and may overestimate growth for old balsam fir if the old-age mortality option is not applied. If a more appropriate growth function is available to the user, this could be substituted for Meyer's equations by simple changes in a program subroutine. The same percentage adjustments could still apply to this new function, which facilitates calibrating simulated growth rates to agree with observed ones.

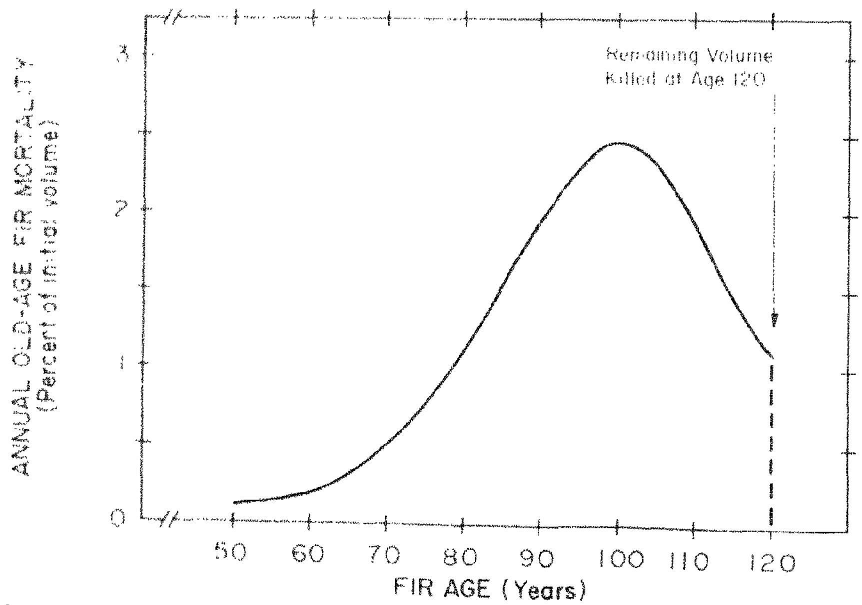


Figure 5.—Optional old-age mortality function for balsam fir (Appendix I).

*User-specified growth rates.*— Instead of using a function to predict growth, users can input their own growth rates directly. This allows an empirical growth function to be constructed with data from remeasured plots that have been stratified by age class. Under this option, net growth (in ft³/acre/year) is specified separately for fir and spruce for the following age groups: 25-30, 31-50, 51-70, 71-90, and 91-150. Stands under age 25 grow no merchantable volume in the model. These rates should include all mortality except that caused by budworm. If the old-age fir mortality function is used, mortality of fir due to wind breakage and blowdown also should be excluded.

As with the Meyer option, the same four adjustment factors can be invoked to make the growth of the simulated forest agree with observed trends. If growth data are derived directly from the forest being simulated, no adjustment should be required, i.e., all factors should be 100 percent. The old-age fir mortality function also can be applied as an option depending on whether the specified growth rates for old fir include mortality. If the growth rates for fir age classes over 50 include all mortality (except budworm caused), old-age mortality should not be applied.

When the model calculates growth and adjusts per-acre stocking, volume is added separately to the pure-species (fir or spruce) "model" acres, not to the entire area in the age class. Therefore, user-supplied growth rates, expressed on the basis of real (not model) acres, must be adjusted to make them compatible with the model-based rates. This is done as follows: the user-supplied growth is multiplied by the factor TA/SA, where TA equals the total area in the age class (by forest type) and SA equals the area allocated to the particular species (fir or spruce). In effect, there is a higher growth rate on fewer acres, but the same total growth results over the entire area in the age class.

When Meyer's function is selected, the rates calculated already are on a pure-species basis, so no adjustment is needed.

### Forest Regeneration

Regeneration is modeled by transferring the areas removed from older age classes (through harvesting or budworm-caused tree mortality) to the young end of the age-class distribution. During this transition, a number of things can happen: areas can change forest type, regeneration can be delayed, or the relative spruce-fir composition of the new age class can be altered. These dynamics are specified entirely by the user on the basis of actual regeneration patterns observed on the forest being simulated.

Areas that originate from simulated harvesting operations are accumulated into two "pools," one for each forest type. Softwood areas can be converted to mixedwood land, which has the effect of reducing the spruce-fir productivity of these acres when they become merchantable at age 25. This is designed to model the component of the real forest where, for whatever reason, long-lived hardwood species become a permanent part of stand composition after harvesting on what was formerly pure spruce-fir land during the previous rotation. Mixedwood cutovers also can be converted to the hardwood type to model the well-established difficulty of regenerating spruce and fir in stands with a strong hardwood component (Westveld 1931). Because the hardwood type is not simulated by the model, these areas are effectively lost from the spruce-fir resource base. Both processes are controlled by specifying separate proportions of the total cutover area in each type that are to be converted annually.

Once the forest-type distribution of the regenerated areas is determined, specified proportions of each can be forced to undergo a simulated regeneration lag. The duration of the lag period (which can range from 1 to 30 years) and the proportion of the total cutover area to be lagged, are specified separately for each type.

From the standpoint of the model, lag periods are the "extra" time after harvesting that is required for the regenerated areas to become synchronized with the developmental track defined by the growth function. In effect, areas undergoing a lag have "negative" ages. For example, assume the growth rate for 31- to 50-year-old fir is set at 50 ft³/acre/year, but that 40 percent of the stands cutover in 1950 do not begin to grow at this rate until 1990, not 1980 as predicted. This can be modeled by specifying a 10-year lag on 40 percent of the acreage. In effect, the lag period allows the stand establishment period to deviate from the "normal" pattern on a certain percentage of the forest, to reflect regeneration failures, effects of competing vegetation, and other factors that are not simulated directly.

When regenerated areas are added to the first age class, either immediately or after undergoing a lag, the relative amounts that become fir or spruce "model" acres are specified by the user. Specifically, the value needed is the proportion of the total regenerated area that is fir; the balance automatically becomes spruce. The same value applies to both the softwood and mixedwood types.

These regeneration processes are primarily natural ones, but can be altered substantially by cultural practices such as cleanings, precommercial thinnings, or herbicide spraying. The assumptions used must mimic the net effects of both natural development and cultural practices on the species composition and stocking when stands reach merchantable size. Thus, the correct input is the expected composition at age 25, not the stocking immediately after harvesting.

Regeneration after budworm-caused mortality is treated differently from that originating after simulated harvesting. Unlike cutover areas, stands killed by the budworm regenerate in a predictable manner. Advanced regeneration, established during the years preceding the outbreak, is not physically affected by budworm attack (as in logging) and tends to retain control of the site after the overstory trees are killed (Ghent et al. 1957; Baskerville 1975). In the model, budworm-regenerated areas remain in the same species and forest-type categories, and do not undergo a lag. If the budworm-caused mortality process were altered such that areas were removed from age classes below 50, this algorithm also would need to be changed to allow more flexibility in the way these areas are handled.

In general, the protection status of regenerated acreage is the same as that of parent stands, that is, areas harvested from protected lands remain under protection after regenerating, even though they probably would not need to be sprayed until later in their development. An exception to this rule is made if no protection is specified for the 0-40 age classes; in this case, all regeneration is added to the unprotected lands. By definition, all budworm-killed areas originate from unprotected land, and regenerate into this category.

Once specified, all parameters controlling regeneration apply without change over the entire simulation. Areas can be added to the resource base by simulated conversion of nonhost (no spruce-fir) forest types. This is accomplished by "planting" a fixed number of acres per year with pure spruce. When these acres become merchantable at age 25, they will grow at the same rate as "natural" spruce areas, as specified by the growth function. All planted areas are regenerated into the protected lands if an outbreak is underway.

If data were available, a more realistic model could be constructed in which these processes vary as functions of the particular harvesting strategies used. For example, advanced regeneration in younger stands, especially of spruce, frequently is insufficient to regenerate a fully stocked stand after clearcutting. To simulate this process accurately, the percentage of the harvested area that undergoes lag, as well as the percentage of fir in the regeneration, could be increased as the age of the stands cut becomes younger.

**Effects of Budworm Attack**

The Green Woods Model does not simulate the actual dynamics of spruce budworm populations. The timing and severity of outbreaks are specified by the user on the basis of current or expected trends. The model predicts only the major effects of budworm defoliation—tree mortality and growth reduction—on the evolving forest structure.

When a simulated outbreak begins, a protection strategy must be specified. This partitions the forest into two categories: protected lands on which there is no tree mortality, and unprotected lands where tree mortality begins after a specified lag period. Growth reduction also begins at rates that can vary between protected and unprotected components of the forest.

*Tree mortality.*—Studies of outbreaks reviewed by MacLean (1980) and historical records for Maine (Seymour 1980) show that tree mortality from uncontrolled budworm outbreaks can vary by host species, forest type, and stand age. The model is structured so that survival on unprotected lands can be specified separately for each of the 12 components of the forest:

| | *Softwood type* | | *Mixedwood type* | |
|---|---|---|---|---|
| *Age class* | *Fir* | *Spruce* | *Fir* | *Spruce* |
| 0–40 | ___ | ___ | ___ | ___ |
| 41–70 | ___ | ___ | ___ | ___ |
| 71+ | ___ | ___ | ___ | ___ |

These categories correspond directly to those used to allocate forest protection. The survival rate is the percentage of each category the user expects to be alive after all budworm-caused mortality is finished.[2]

Because the budworm feeds primarily on current foliage of fir and spruce, tree mortality is a gradual process that extends over many years, as old foliage is consumed or lost to natural attrition and is not replaced. This is modeled by distributing the total mortality (as given by the user-supplied survival rates) over a 6-year period according to the following annual rates:

| *Year of mortality sequence* | *Proportion of total mortality (unadjusted)* | *Adjusted for previous mortality* |
|---|---|---|
| 1 | 0.05 | 0.05 |
| 2 | .10 | .105 |
| 3 | .20 | .235 |
| 4 | .25 | .385 |
| 5 | .30 | .750 |
| 6 | .10 | 1.000 |

[2] An earlier version of the program used four reverse logistic equations to predict mortality by species and forest type as a function of age. Severity factors were used to calibrate these functions, but recent tests have shown them to be too restrictive, primarily because they cannot be made to predict the high mortality rates that have been observed in young stands during the current outbreak.

In stands not previously attacked by the budworm, trees begin to die 3 to 5 years after the onset of defoliation (Belyea 1952; Blais 1958; Baskerville and MacLean 1979; Maclean 1980). However, this lag period may be substantially shorter for trees removed from protection that do not have a full complement of foliage. In the model, the time between the onset of the budworm outbreak and the first year of tree mortality on unprotected lands can range from zero to 8 years. Separate mortality lag periods can be applied to spruce and fir, and can be changed each time lands are withdrawn from protection.

The actual mechanism used to simulate mortality depends on the age of the affected areas. In age classes over 50, areas are "killed" by removing them from the vulnerable age classes and "regenerated" by adding them back to the first age class the following year. The scale and spatial distribution of mortality are not modeled explicitly. Simulated budworm-caused mortality removes area formerly allocated to the dead mature trees and transfers it to 1-year-old advanced regeneration that begins to grow normally. In effect, this creates two age classes (the survivors and regeneration) where only one existed prior to the budworm attack (Ghent et al. 1957). The volume lost to mortality is calculated by multiplying the area killed by its corresponding stocking per acre. Thus, in age classes over 50, the proportions of the area and volume killed are equal, which leaves the surviving model area stocked at the preoutbreak level.

In younger spruce-fir stands, budworm mortality has somewhat different effects. Advanced regeneration is less abundant or might be totally deficient. Due to the lower vulnerability of young trees, only a portion of the overstory might be killed. Unless it is unusually severe, budworm mortality in these age classes resembles a heavy thinning; the surviving overstory is understocked, but no new age classes are regenerated (Baskerville and MacLean 1979). This is modeled by removing only *volumes* from age classes below 50 in which there was budworm mortality; areas are unaffected and continue to advance in age. Because less volume remains on the same area, stands in these age classes become understocked. Although growth may return to preoutbreak rates after mortality is complete, this understocking persists until the age classes are harvested.

This algorithm for simulating mortality is not without certain deficiencies. Because all age classes under 25 have no merchantable volume, they are essentially immune to budworm effects. Experience from the current outbreak shows that stands in this age class can suffer high mortality if defoliation persists for a sufficiently long period. Also, the threshold of age 50 for determining whether areas regenerate after budworm mortality is somewhat arbitrary. In practice, this would be affected by past silvicultural treatments and the current stocking of the younger age classes. The model could be modified to remove area from *all* age classes after mortality, or perhaps more appropriately, to put all areas lost to mortality from young age classes through a regeneration lag. The basic problem here is not the inadequacy of the model to mimic the real world, but a lack of research and experience to describe the underlying dynamics.

In the model, areas that survive the 6-year sequence of tree mortality cannot sustain another tree-killing outbreak for the remainder of the simulation. This feature was incorporated on the grounds that a single outbreak usually would purge the unprotected forest of its vulnerable components, rendering it invulnerable to further tree mortality. This may not be realistic for stands that are attacked by the budworm when young and again during a second outbreak much later in life. Clearly, most if not all of the trees over 70 years old in the present spruce-fir forest survived the 1910–20 outbreak; many of these same trees, especially the older fir, are now being killed in the current outbreak. However, this does not prevent a realistic simulation of mortality in the current outbreak, because the model does not "know" that these older stands have a history of budworm attack. It would effect only the vulnerability of the now young age classes to an outbreak that might occur during the 21st century.

Because areas that have survived tree mortality are stored separately in the program, this algorithm could be changed to allow areas to experience multiple tree-killing sequences. A provision could be added to transfer areas formerly attacked by the budworm to the vulnerable components of the forest, perhaps only after a minimum period of years had elapsed since the previous outbreak.

*Growth reduction.*—Forest growth can be reduced to account for the effects of budworm defoliation. Four user-supplied factors—one each for fir and spruce on both protected and unprotected lands—are used to reduce growth proportionally over all age classes. Growth reduction begins automatically 2 years after the onset of an outbreak, and continues for a period which can vary among these four components of the forest. After mortality on unprotected lands is complete, growth reduction can still be applied. With this provision, users can simulate reinfestation from surrounding protected lands, or model the effects of understocking (resulting from mortality) which reduces growth in surviving uninfested stands.[5]

Because the model uses *net* growth rates (including negative effects of natural mortality), growth-reduction factors have a different interpretation between protected and unprotected lands. The appropriate factors for *unprotected* fir and spruce should include only the effects on surviving trees; budworm mortality is simulated separately as described previously. Specifically, the correct input is the difference between the actual accretion of surviving trees and the rates expected under normal (nonoutbreak) conditions.

Insecticide spraying usually protects sufficient foliage to prevent widespread tree mortality, but there still is some defoliation that can reduce growth (Kleinschmidt et al. 1981). On protected lands in the model, no budworm-caused tree mortality is simulated, so the appropriate reduction factors must take into account both lost accretion and any net increase in tree mortality due to budworm defoliation in the protected stands.

[5] There are two important differences between this alogrithm and the previous version of the model in use during 1980-81. Formerly, growth reduction continued indefinitely on all lands so long as some acreage remained under protection. The new feature was incorporated to allow a simulated "collapse" of budworm populations. Also, in the old version, growth on unprotected lands after tree mortality was complete was automatically reduced at the same rate as the protected lands, subject to a function that weighted growth according to the proportion of the total forest under protection.

## Forest Management Practices

### Forest Protection Against Budworm

The goal of forest protection is to prevent or limit the destructive effects of uncontrolled budworm outbreaks. In the model, different levels of forest protection can be allocated to each forest type and species, and to age classes 0–40, 41–70, and 71+. By protecting various proportions of the total forest area in each of these categories, the user defines a "protection zone" where there is no budworm-caused tree mortality and growth reduction can be less severe than on the unprotected lands.

Although protected and unprotected lands are often combined in model output, all attributes of forest area are stored internally in separate arrays for each. These characteristics evolve independently in response to the user-controlled dynamics of a particular simulation. As a result, protected and unprotected lands develop unique age structures, stocking levels by age class, and forest type distributions.

A protection strategy is needed only if a simulated outbreak is underway. Once a protection zone is specified during an outbreak, tree mortality begins on the remaining (unprotected) area. Protection strategies can be changed up to six times during a simulation, to withdraw area from or add it to the protection zone. If changes result in a net reduction in protected acreage, areas are transferred to the unprotected category and tree mortality begins soon thereafter according to the specified lag period.

Through successive reductions in the protection zone, areas can be at different stages of deterioration in the 6-year mortality sequence. The protection zone can be increased during an outbreak only if unprotected acreage is available which has not passed the third year of mortality. When such an increase is specified, the mortality process is halted, and the area is transferred to the protection zone. Areas beyond the third year of mortality are assumed to be too badly deteriorated in tree condition to recover, and cannot be retrieved.

With the current state of the art, protecting the spruce-fir forest against the budworm is accomplished almost entirely by annual insecticide spray programs. Current protection strategies are designed primarily to prevent tree mortality, which usually does not require that all infested areas be treated annually. The protection zone, as defined by the user, is intended to represent the total area where such programs are applied successfully, plus any uninfested areas where it is not needed—the total area on the forest in which there is no budworm-caused mortality. Thus, the area in the protection zone bears no direct relationship to the acreage sprayed annually, which is determined by the particular status of budworm populations and tree condition in a given year. For example, if it is determined that, on average, areas need to be sprayed every other year to prevent mortality, then the protection zone would be twice the size of the average annual spray program.

*Targeting protection.*—In practice, aerial spraying is applied to "real" forest acres, not to the pure-species areas used by the model. Within each forest type, the spruce and fir areas targeted for protection must be specified in proportion to their volumes per acre to reflect the species composition of stands in the protection zone. Targeting on one species to the exclusion of the other can still be done, but not to an intensity beyond that which can be achieved with the smallest operationally feasible spray block. For example, specifying a protection zone that includes only fir is not a feasible strategy. In the model this would represent a situation where all fir trees were sprayed but the spruce trees in the same stands were not. In practice, protecting the desired amount of fir would require spraying stands that also contain some spruce. To account for the way the model simulates growth and mortality, this additional area occupied by spruce trees also must be included in the total protection zone.

Managers usually begin with the total acreage in a protection zone, then work backward through a stand-by-stand hierarchy to arrive at the correct proportions of each species to protect in a simulation. Details of this process are shown in the section on applying the model.

### Timber Harvesting

The algorithms used to simulate harvesting can replicate virtually any operational strategy. Users control the following variables, singly or in combination:

1. Total volume harvested.
2. Percentage of spruce or fir in the total cut.
3. Percentage of the total cut to come from dead trees (salvage).
4. Percentage of the total cut to be allocated to protected or unprotected lands.
5. The age of the youngest trees considered merchantable for both spruce and fir.
6. Intensity of discrimination against the oldest wood within the merchantable age classes.

Harvesting strategies can be changed annually, up to 30 times during a simulation.

The total volume of spruce and fir to be harvested is specified in merchantable cubic feet, with no distinction by size or product class. This allowable cut should equal the total drain from the merchantable spruce-fir inventory that results from all harvesting operations; the portion actually utilized is not relevant.

If a budworm outbreak is under way and some lands are under protection, users can target simulated harvests onto protected or unprotected lands by specifying the percentage of the total volume to cut from the unprotected acreage.

*Species discrimination.*—Harvests can be targeted on spruce or fir to simulate strategies that attempt to exploit the differences in growth or vulnerability between these species. We define discrimination "against" fir, for example, as a strategy that attempts to accelerate the harvest of fir to favor spruce and increase its overall composition in the forest. Such discrimination against one species can be accomplished in two ways: (1) clearcuts targeted on stands dominated by one species, bypassing stands of the other; (2) partial cuts that remove primarily one species, leaving residual stands dominated by the other.

Simply specifying the volumes of each species to harvest is not sufficient to define a level of discrimination. Discrimination is a relative phenomenon; it can be defined only by comparing the proportions of each species harvested to their abundance in the entire forest. For example, if 50 percent of the harvest is fir in a forest that also is 50 percent fir, no discrimination is being practiced, since this percentage would arise by allocating harvests entirely at random throughout the forest. However, the same percentage harvested from a forest that is 80 percent spruce would represent an intense discrimination against fir.

In the model, a "no-discrimination" harvesting strategy is defined as one in which the proportion of fir in the harvest equals the proportion of fir in the forest. In Figure 6, this is represented by the 45-degree line (slope = 1.0). Discrimination against a particular species represents the "extra" proportion of that species in the harvest above its share of the inventory. The discrimination factor is defined at the point where spruce and fir make up equal proportions of the inventory (a 50:50 ratio), but is adjusted through an exponential function (Appendix I) to account for the fact that harvest discrimination is more difficult as either species dominates the other. For example, a 15-percent discrimination against fir applied to a forest that is 50 percent fir would generate a harvest of 65 percent (50 + 15) fir. However, in a forest that is 20 percent fir, the same strategy would produce a harvest of 28 percent fir, only 8 percent more than the inventory (Fig. 6).

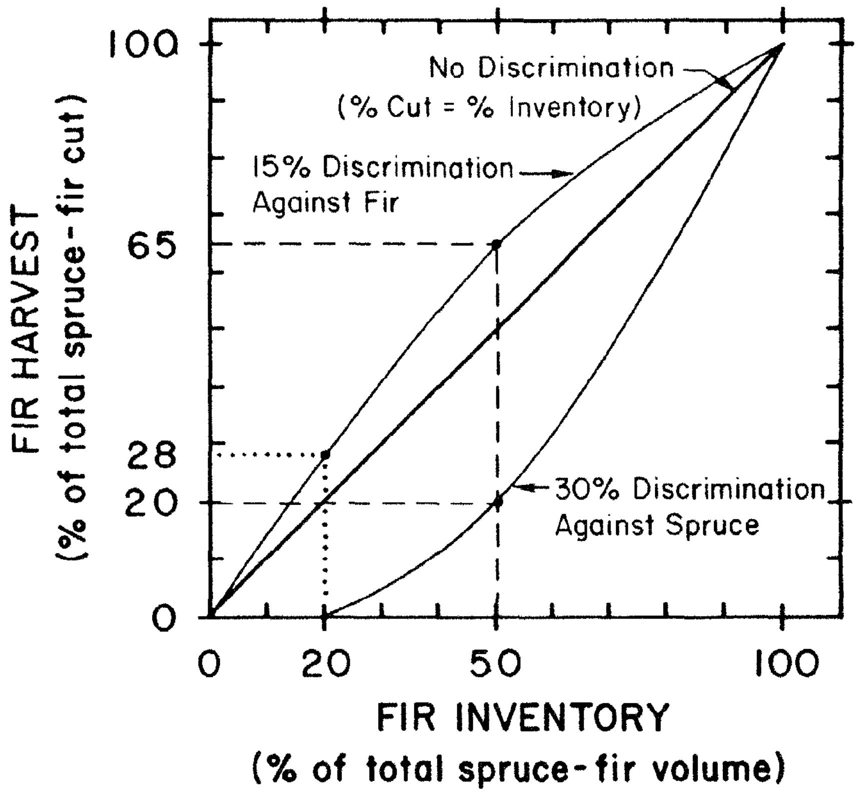


Figure 6.—Schematic of algorithm used to simulate harvesting strategies which discriminate against fir or spruce (Appendix I).

*Merchantability.*—With present-day utilization, stands below a certain age usually are regarded as inoperable. Even though they contain trees of merchantable size, the cost of harvesting and subsequent processing outweighs the value of the finished products. Users can simulate these limits by setting a minimum age for operable stands below which no wood will be cut even though volumes are physically present. These low age limits can be specified separately for spruce and fir, and are set once for an entire simulation.

Within the age classes considered operable, users can discriminate against older wood by allocating the harvest to only a specified oldest proportion of the operable inventory. Formally, the discrimination parameter is defined as:

$$\frac{\text{OLDFOR}-\text{YOUNGCUT}}{\text{OLDFOR}-\text{YOUNGOP}}$$

where OLDFOR equals the oldest age class in the forest, YOUNGOP equals the youngest stands considered economically harvestable, and YOUNGCUT equals the youngest stands that a manager initially wishes to harvest, even though younger stands are considered operable and would be cut if necessary. If YOUNGCUT = YOUNGOP, the discrimination parameter = 1.0 and harvests will be allocated uniformly to all age classes above the operable age limit. AS YOUNGCUT approaches OLDFOR, the harvest strategy becomes an "oldest first" rule, with intense discrimination against older wood.

For example, a manger of a forest containing stands up to age 100 determines that the youngest stands he can harvest are 50 years old, but initially would like to harvest stands only above age 70. To simulate this strategy, he would specify a harvest allocation to 60 percent [(100-70)/(100-50)] of the oldest age classes. As the older stands gradually became exhausted, the same percentage would still apply, but over a more limited range of ages. At the point in the simulation where the oldest wood was age 80, the youngest wood harvested would come from age class 62 [80-0.6(80-50)]. If insufficient wood is available in the oldest specified proportion to meet the harvest goal, the program continues to accumulate volumes below the calculated age limit, overriding the strategy to avoid a shortfall.

*Optimum rotation age and regulation index.*—Users specify the rotation age they would employ if the forest were fully regulated by age class. This age is used only to compute an index of forest regulation; it has no role in controlling harvesting operations. The Regulation Index represents the departure of the actual forest structure from the ideal "normal" forest, which contains equal areas in all age classes below the specified rotation age, and none older. It is similar to the coefficient of determination ($r^2$) used in regression analysis, and is calculated as follows: for each age class, the actual area is subtracted from the expected area in the hypothetical "normal" forest. The absolute values of these differences are summed over all age classes and expressed as a proportion of the total forest area. The resulting index is, in effect, the proportion of the forest that is in the wrong age class relative to the manager's goals.

It should be emphasized that the optimum rotation age is used only to calculate the regulation index, *not* to control simulated harvesting activities. Actual harvests by age class are governed entirely by minimum operable age and percent allocation to the oldest wood, as described previously; the optimum age is ignored.

*Salvage.*—During a simulated budworm outbreak, volumes killed on the unprotected lands are accumulated by species and age class into a "pool" that is temporarily available for salvage. Each year, dead wood is "aged" and reduced in volume according to the following factors:

| *Years since death* | *Percent of original volume still usable* |
|---|---|
| 1 | 100 |
| 2 | 95 |
| 3 | 85 |
| 4 | 70 |
| 5 | 0 |

These simulated decay rates were derived from Field and Shottafer (1979) to account for losses to sap rots, stem breakage in logging and other factors that reduce yields when dead wood is utilized.

Salvage is simulated in two ways: (1) by specifying that a certain proportion of the harvest must consist of dead wood, if any is available, or (2) that dead wood be cut in proportion to its occurrence on the unprotected lands. In the first option, the salvage proportion can be regarded as a goal or a constraint, depending on the needs of the user. Volumes salvaged replace equivalent volumes of "green" wood from the unprotected lands.

*Areas harvested and partial cutting.*—Simulated harvest areas are equivalent to the actual cutover areas only where operations remove all merchantable spruce and fir trees from the stand (complete clearcuts). If a portion of the total harvest volume is derived from partial cuttings where spruce or fir trees are left in a residual stand, the model will underestimate the actual acreage operated. In the partial-cutting case, the model will remove volume from and regenerate only that portion of the stand actually occupied by trees harvested, not the entire stand area. This has no effect on simulated growth and development of the residual "areas" but does underestimate the actual total area on which operations must be conducted. Volumes removed per acre also will be overestimated by a proportional amount.

The model will reproduce accurate harvested acreages for operations in mixedwood stands that remove all spruce and fir but leave hardwoods. The model does not simulate hardwood trees; the entire area in mixedwood stands is, in effect, allocated to spruce or fir trees by stocking the mixedwood type at lower volumes of spruce-fir per acre. Thus, a given volume of wood harvested from mixedwood land removes more simulated acreage than if the same volume were harvested from the better stocked softwood type.

## How the Model Simulates Forest Development

Before applying the model to an actual situation, it might be helpful to illustrate how each of the processes described is simulated by the model. Three examples are presented: Natural growth and development (no cutting or budworm attack), budworm attack at age 60 with no protection, and harvesting at age 60 with a 10-percent discrimination against fir. Each situation begins with a forest composed of 1,000 acres of softwood type, all in a single age class. Species composition was set at 50 percent fir, and simulations are carried out using 50 percent of Meyer's function to grow the forest. Note how the species composition and age structure of this forest change in response to both natural processes and man's activities.

Because this hypothetical forest contains area in only one age class, these simulations represent a special case in which the time elapsed since the beginning of the simulation equals the "age" of the forest. In this sense, the 1,000-acre, single-aged "forest" can be considered to be a "stand" whose age is given by the "year" axis. In a realistic simulation of a forest with many age classes, this would, of course, not be true. This example is presented to illustrate how the important dynamics are controlled by age, which is obscured when several age classes are combined.

### Natural Forest Development

This simulation begins with 500 fir and 500 spruce "model" acres, all in age class 1. In year 25, growth of merchantable volume begins, with both species growing at the same rate until year 50 (Fig. 7). At this time, the old-age fir mortality function begins to kill small portions of the total fir volume. By about year 70, fir mortality exceeds accretion and net growth on this area becomes negative. The fir area becomes progressively understocked, resulting in a declining yield.

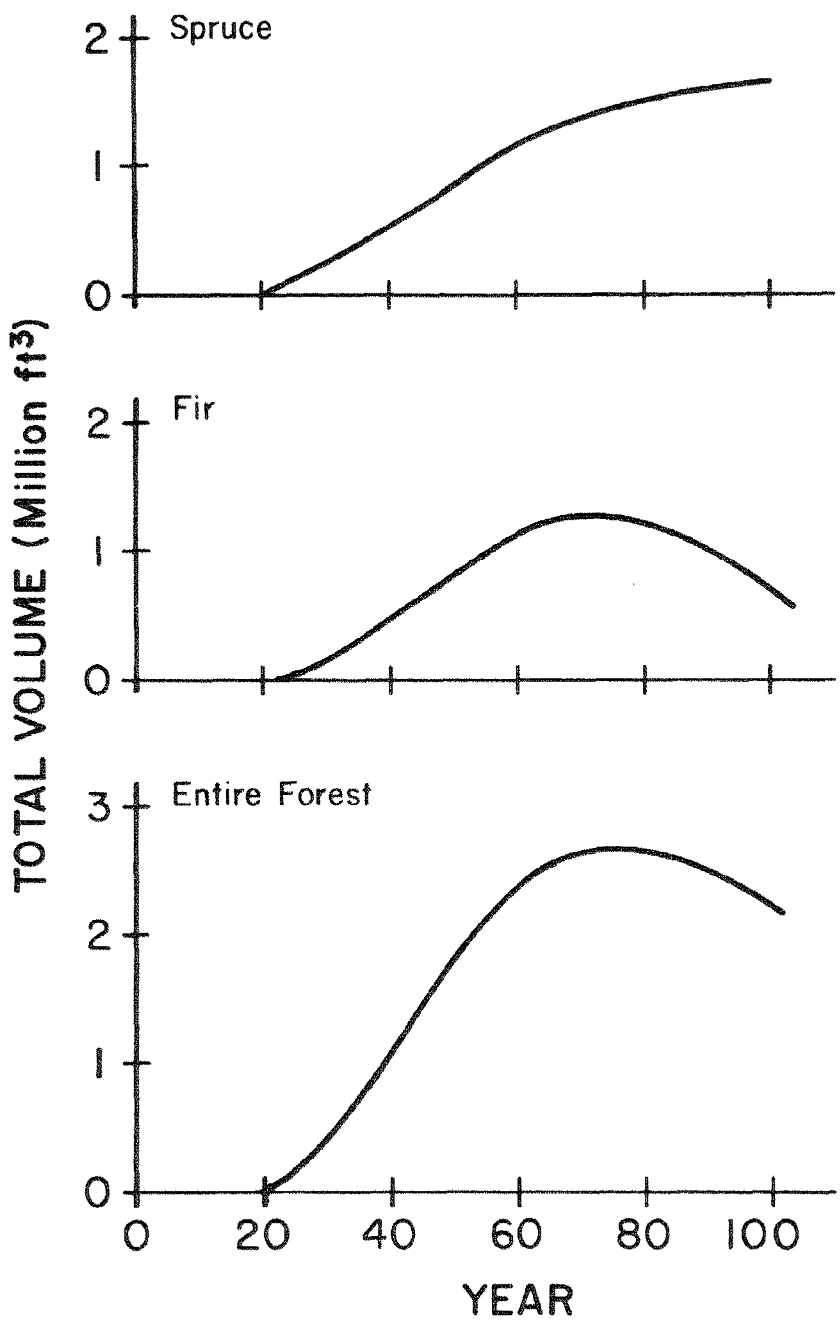


Figure 7.— Simulated growth and development of a hypothetical 1,000-acre spruce-fir forest (50 percent fir, growth = 50 percent of normal), no cutting or budworm attack.

No such mortality is applied to spruce, which continues to increase in volume, but more slowly as the area ages. Soon after year 70, the decline in fir exceeds gains in spruce, so growth on the entire 1,000-acre forest becomes negative. If the simulation were carried further, without harvesting or budworm attack, the entire fir area would be regenerated in year 120 when only 5 percent of the original volume would remain.

**Budworm Attack in Year 60, No Protection**

In this example, normal growth proceeds as above for 60 years when a budworm attack begins. Survival rates were set at 60 percent for spruce and 20 percent for fir. Fir mortality begins 2 years after the onset of the outbreak; spruce begins to die 2 years later (4 years after the outbreak begins). During the 6-year mortality sequence that follows, growth is reduced to only 20 percent (for fir) and 50 percent (for spruce) of the preoutbreak rates.

The yield curves for both species decline sharply as mortality proceeds (Fig. 8). Mortality ends in years 68 and 70 for fir and spruce, respectively, growth reduction stops, and normal (preoutbreak) growth resumes. Three hundred acres of spruce (60 percent of the total) and 100 acres of fir (20 percent) survive the outbreak, and continue to advance in age. The old surviving age class is stocked at the same level per "model" acre as if no mortality had occurred, but occupies fewer acres. This causes the entire forest to be understocked.

During the outbreak, the remaining area—200 spruce and 400 fir acres—is "killed." All merchantable volume on this area is lost as tree mortality. These areas are regenerated, forming a new age class but remaining in the same species category. The simulated budworm mortality has, in effect, created a two-aged structure over the entire 1,000-acre forest, which originally consisted of only one age class.

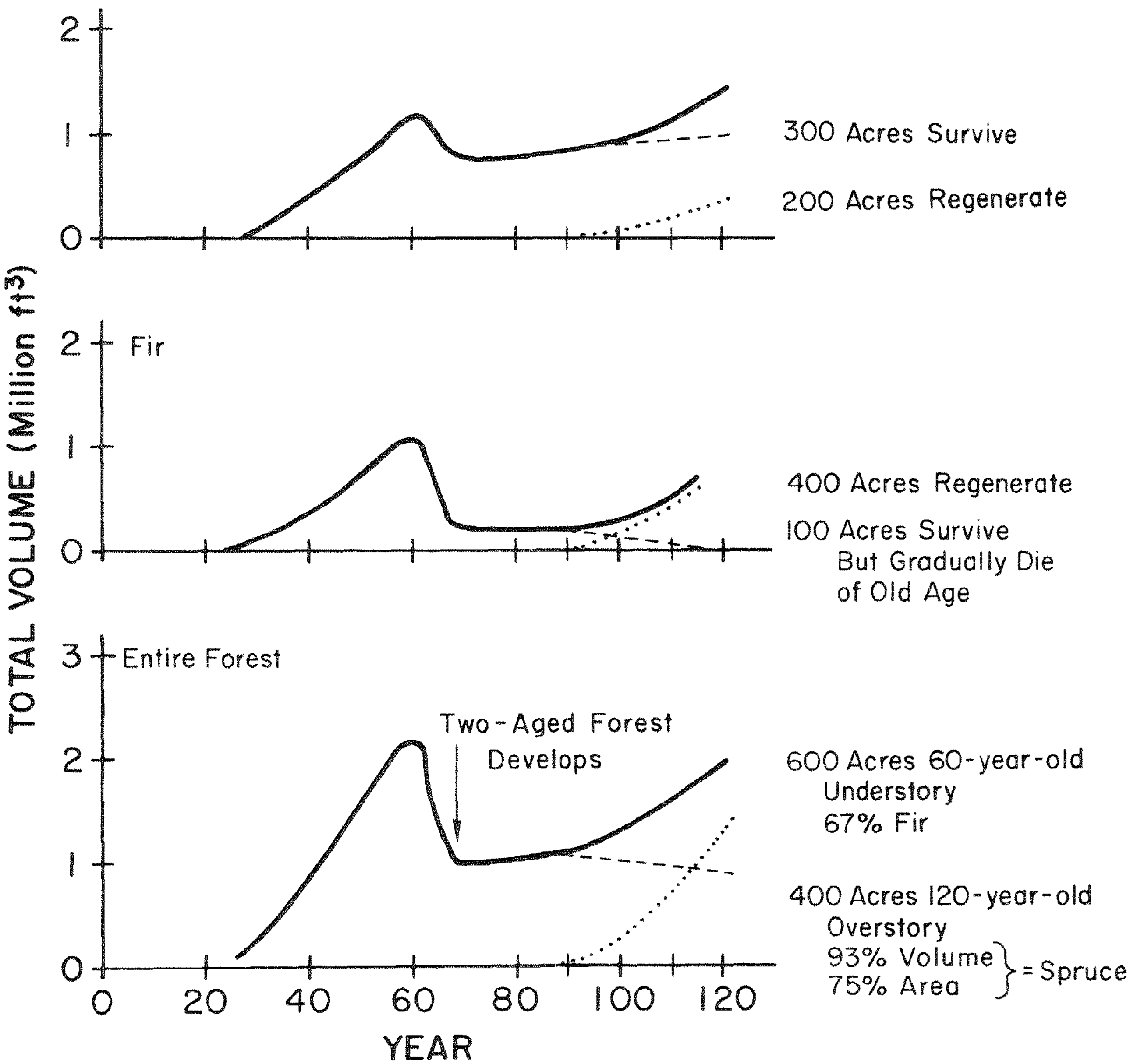


Figure 8.—Simulated growth and development of a hypothetical 1,000-acre spruce-fir forest (50 percent fir, growth = 50 percent of normal), attacked by budworm in year 60.

In the postoutbreak forest, the surviving fir area continues to lose volume due to old-age mortality. On a forestwide basis, however, these losses are offset by growth of surviving spruce, which now makes up 75 percent (300 of 400 acres) of the old-age class. Surviving areas continue to gain volume until about year 90 when old-age fir mortality finally exceeds growth of spruce (Fig. 8, declining dashed line). However, growth on the entire forest remains positive, and even begins to accelerate as the new budworm-origin age class (dotted line) becomes merchantable. Sixty percent of the forest area—600 "model" acres—is now between 15 and 25 years old. This age class grows at the same per-acre rate as its predecessor did initially, though its species composition has changed in favor of fir.

At the end of the simulation, the total area of each species is the same as at the beginning, but the age and volume structures have changed significantly. Ninety-three percent of the volume and 75 percent of the area in the 120-year-old surviving age class is spruce, whereas two-thirds of both the volume and area in the budworm-origin age class, now age 60, is fir. If protection had been applied during the outbreak period, more area would have survived depending upon the strategy used, and less area would have been regenerated.

**Harvest Half the Volume in Year 60**

This example begins with the same initial conditions as the previous two cases. In year 60, a harvest of 1,068 milion $ft^3$—half the standing volume—is made with a 10-percent discrimination against fir. Composition of the regeneration is set at 90 percent fir.

As described previously, the species composition of the harvest is determined by adding the user-specified discrimination level to the percentage of fir in the inventory. In this example, a 10-percent discrimination against fir is added to an inventory of 50 percent fir, which gives a harvest of 60 percent fir (641,000 $ft^3$). The balance (427,000 $ft^3$) is from spruce. At year 60, old-age fir mortality has not yet become important, so the per-acre stocking of both species is identical. Thus, areas harvested are directly proportional to the volumes removed. In this example, harvesting half the volume removes and regenerates half, or 500 acres, of the total forest, leaving an equal area in the old age class. Sixty percent (300 acres) of the harvest was fir; 200 fir and 300 spruce acres were left as a residual.

The residual areas follow the same development pattern observed in the two previous examples: slow increase in volume initially, then a decline as spruce growth slows and fir mortality increases with advancing time and age (Fig. 9). The major difference is in the regeneration response. Here, 90 percent of the area harvested (450 acres) regenerates to fir, leaving only 50 acres in young spruce. Overall forest composition changes from 50 to 65 percent fir as a result. This did not occur in the previous example (Fig. 8) because areas do not change species composition after budworm mortality.

## Summary

Using the model to simulate more elaborate forest structures and management strategies is a straightforward extension of the processes illustrated. Forecasts could be done entirely by hand if it were not for the tremendous volume and repetitive nature of the calculations and bookkeeping. The algorithm was programed only to expedite these tedious procedures; it *does not* determine particular outcomes. The number of possible interactions among forest structure, natural processes, and management activities is virtually infinite. However, because the user specifies the rate and timing of each process, as well as the initial forest structure to which they are applied, all such effects are explicit. Within broad limits, the user essentially creates a unique model of his or her own special situation without being constrained by particular "built-in" assumptions that he or she may find unacceptable. Default procedures occasionally are needed to cover special cases.

It should be apparent from the examples cited that the model is not limited to forests composed entirely of even-aged stands. Any stand structure can be accommodated if the different age classes are separated when initializing the forest for simulation. New age classes are regenerated by the model whenever a disturbance removes some portion of the area from merchantable age classes, just as in nature. The 1,000-acre forest used in the examples is arbitrary. These simulations could just as easily be viewed as a 1-acre, even-aged "stand" which gradually develops a two-story structure after being attacked by budworm, harvested, or allowed to grow old and die naturally.

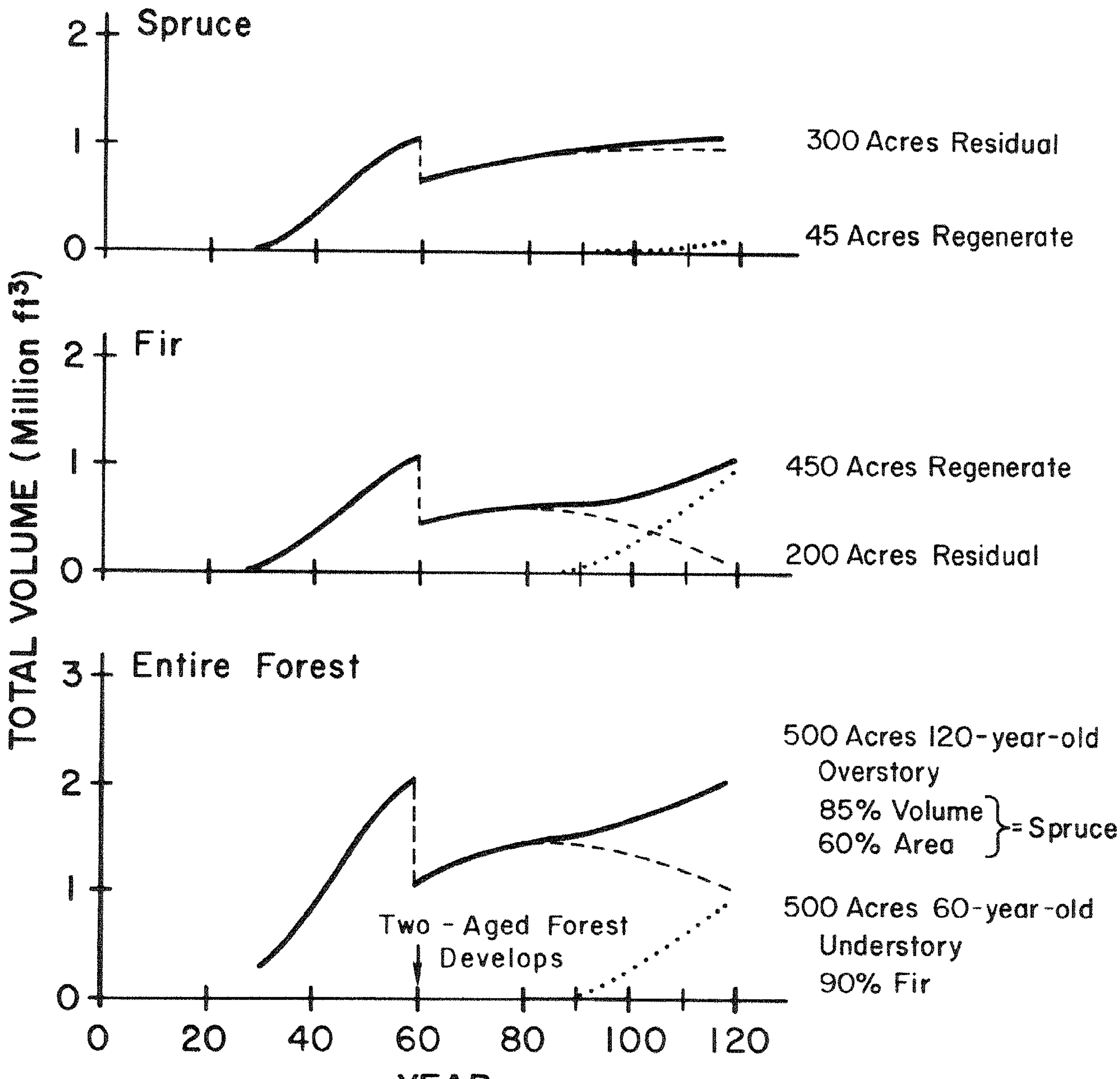


Figure 9.—Simulated growth and development of a hypothetical 1,000-acre spruce-fir forest (50 percent fir, growth = 50 percent of normal), with half of the total volume harvested in year 60 using a 10-percent discrimination against fir.

Misunderstandings sometimes can develop when age-class distributions are derived from traditional forest inventory plots. The basic problem is that the area represented by a single plot probably bears no relationship (except for perhaps a coincidental one) to the actual scale of the overstory-removal and regeneration processes in spruce-fir forests. Consider the case in which the basic sampling unit, for example a 1-acre plot, is occupied by trees in each of two 1/2-acre age classes. One originated after a commercial clearcut 80 years ago, and second started 20 years later after a tree-killing budworm outbreak. By conventional definitions, this plot, or the stand in which it is located, would not be considered even-aged because the majority of the stocking cannot be assigned to a single age class. Yet, as illustrated in Fig. 8, the model will accurately reproduce such a stand structure, and can accept such data as initial input. If the spatial distribution of the mortality, harvesting, and regeneration phenomena are ignored, the model accurately replicates the true forest dynamics.

In lieu of improved mensurational procedures, approximations can be used to derive an age structure from existing data. The key is to estimate the area occupied by each age class, if more than one is present. These areas are then separated in the model even though they are intermingled within the same stand. An example of how to deal with multiple age classes within stands is presented in the next section.

## Wood Supply-Forest Protection Analysis

This section discusses how the model can be used to assist managers or policy analysts who are faced with problems connected with budworm-infested spruce-fir forests. Emphasis is on deriving model inputs from conventional forest inventory information that is commonly available to resource managers. We assume that potential users already have structured their problems for analysis and need only technical guidance in obtaining or adapting their own information.

The example is structured around a special interactive computer program (Appendix II), which facilitates creating and modifying the basic input data file. Input data are organized into seven main categories on a convenient summary form (Appendix III) that follows exactly the order of entry in the interactive program. Special worksheets (Appendix IV) have been prepared to aid in translating inventory data into the required model inputs.

Before specific technical details are discussed, a caveat on model use is necessary. The structure of this model allows an exceedingly diverse array of "what if" questions to be posed. This extreme flexibility can be a great asset under the proper circumstances, but can also be abused by careless, uncritical users. Analysts must exercise care to ensure that input data are as realistic as possible; the model will readily accept biologically impossible combinations of forest dynamics or artificial forest structures. Where information is poor and assumptions must be made, results must be interpreted with caution. When faced with uncertainty, users always should view the results in the following manner: "*If* the dynamic processes proceed as I have assumed, *then* the results are the best estimate of what I can expect the future to look like."

## Available Information

This example illustrates how the model can be applied using a forest-type map and associated inventory data. Township 14 Range 16 in northern Maine near St. Pamphile, Quebec, was part of a demonstration area established by the Green Woods Project in cooperation with Seven Islands Land Co., which manages the town. Its history, current forest structure, and management problems are typical of a broad region in Maine, and it illustrates how the model can be used to design harvesting and protection strategies to cope with the current budworm infestation.

In 1976, a forest-type map was prepared for the town by J. W. Sewall Co., Old Town, Maine. Stands were classified on black and white copies of color infrared aerial photography (1:15,840) according to forest type, height class, and density. The following categories were used:

| *Broad forest type* | *Forest stand code* | | |
|---|---|---|---|
| | *First* | *Second* | *Third*[a] |
| S | Softwood code | Softwood code or "/" | Any code |
| SH | Softwood code | Hardwood code | Any code |
| HS | Hardwood code | Softwood code | Any code |
| H | Hardwood code | Hardwood code or "/" | Any code |

[a] The third species code, if present, represents an important component of the stand described by the first two codes.

*Height* (feet)

1 = 0–15
2 = 15–30
3 = 30–50
4 = 50 +
5 = Irregular/storied

*Crown closure*

A = 81–100
B = 61–80
C = 31–60
D = 0–30

*Forest ground conditions*

sw = Wet, swampy
ry = Rocky
sr = Steep and rocky
II = Site II

*History of stand*

br = Burn
wf = Windfall
pc = Partial cut
pl = For logs
pp = For pulp
cc = Clearcut
di = Disease/insect
of = Agricultural
pn = Plantation

Where possible, individual species were distinguished, and the stand history, if known, recorded. Each stand was assigned a unique number and its area determined. All information was encoded in a computer file, with individual records for each stand.

During 1979 and 1981, 286 10-BAF prism plots were taken to determine volume per acre by species. Sample trees of each species were bored to determine age (total age or age since release). Milacre regeneration plots were taken to assess stocking on cutover areas. Plots were distributed among 25 separate strata to characterize each according to factors influencing forest growth and vulnerability to budworm damage.

## Derivation of Input Data

Deriving model inputs is a straightforward process. The necessary steps are given below in the order required by the interactive program. A numerical code is used to link the text with the specific item on the input summary form (Appendix III).

### Step 1

Specify the simulation parameters (Appendix III, 1.1 to 1.7). These variables control program execution and determine the types and frequency of output. The option used to stock and grow the forest depends on the nature of the data available to the user. In our example, the function option was selected for both purposes, though either could have been used to initialize the simulated forest.

### Step 2

Divide the forest area into strata that are similar with respect to potential growth and development, budworm vulnerability, and application of forest protection and harvesting. On T14 R16, analysis revealed that the forest structure could be characterized effectively for simulation by combining the 25 sampling strata into three categories:

1. Mature, fully stocked stands with no history of cutting or major disturbance since 1950 (S3A, S3B, S4A, S4B stands).
2. Stands that had been partially cut since 1950 and had developed a two-story structure (typically S4C, SH4C stands).
3. Stands that had been clearcut since 1950, with essentially no merchantable trees remaining on the site and all growing space allocated to regeneration (S3D, S4D, SH3D, SH4D stands).

**Step 3**

Determine areas, merchantable cubic-foot volumes per acre for spruce and fir, and the age classes represented in each stratum (Worksheet 1). On T14 R16, the volume of fully stocked, mature softwood stands averaged 1,913 ft³/acre, 54 percent of which was fir. Merchantable trees ranged in age from 50 to more than 100 years from release.

A total of 988 acres of softwoods was recorded as having been partially cut since 1950, primarily by diameter-limit rules which varied by species. These stands have a two-story structure, with a residual overstory of old trees stocked at 1,242 ft³/acre and a new age class of advanced regeneration developing in openings created by the partial cuts. These two age classes must be separated in the model, ideally by measuring the actual areas occupied by trees in both age classes. In practice, this is difficult to determine directly, so an alternative approach is used. The volume of the overstory in this stratum averages only 65 percent (1,242/1,913) of the stands considered to be fully stocked. If it is assumed that the portion of the stand actually occupied by mature trees is stocked at the same level as the uncut fully stocked stands, this would give 65 percent of the area (641 acres) to the 60–100 age classes, leaving 35 percent (347 acres) to allocate to the regeneration in the 0–30 age classes.

Many of the softwood stands clearcut since 1950 fall into the S4D type, which contains virtually no overstory; most merchantable trees were cut in the logging operation, or have blown down since. This acreage was allocated entirely to the 0–30 age class with no volume per acre.

The corresponding strata in the mixedwood type were treated identically, and should be self-explanatory.

**Step 4**

Distribute the area in each forest type by 10-year age class. Enter the total stratum areas at the bottom of each column (the Total line) in Worksheet 2. For each stratum separately, determine the proportion of the total area that falls into each 10-year age class. If ages were assigned to plots in the field, this is simply the distribution of plots by age class in each stratum (weighted appropriately by the sampling scheme used). If no ages are available, one can simply specify percentages that seem to reflect the history of major stand-creating disturbances on the area. For example, records indicate that T14 R16 was heavily logged between 1870 and 1890 for old-growth spruce and pine, and then suffered severe mortality during the 1910–20 budworm outbreak. These correspond to the 91+ and 61–70 age classes, respectively, in 1980. Most of the area clearcut in the last 30 years originated during the 1970's, and was allocated accordingly.

For each stratum, multiply the total area by these proportions to obtain areas by age class. Then for each forest type (softwood and mixedwood), add across all strata to obtain the total acreage in each class. Divide these areas into the total type area (Appendix III, 2.1 and 2.2) for the overall age-class distribution (2.3 and 2.4) needed by the model. The resulting age-class distribution for the softwood type is given in the "percent" column under all strata on Worksheet 2 and is shown in Figure 10.

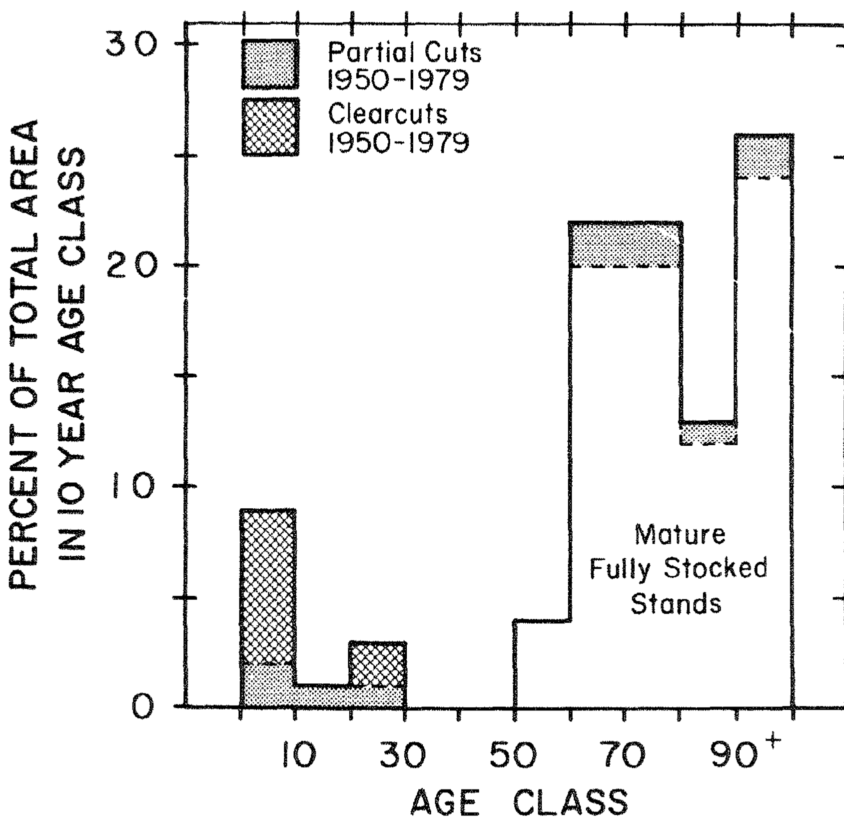


Figure 10.—Age structure of T14 R16.

At this stage, users can stock the forest with the percent-of-normal option or supply actual volumes per acre. This example illustrates the percent-of-normal option.

**Step 5**

Estimate percent stocking by age class. From the age structure (Appendix III, 2.3 and 2.4) derived in Step 4 (Worksheet 2), calculate a weighted average age for all classes that contain volume. Determine the volume per acre of a fully stocked stand of the same age from Meyer's tables (Appendix I). Remember to use Site Index 50 for the softwood type (Appendix III, 2.10) and Site Index 60 for the mixedwood (2.11). Divide the normal stocking from Meyer's tables into the actual volume per acre of spruce and fir to obtain percent stocking for all merchantable age classes.

For example, the average age of merchantable softwood area on T14 R16 is nearly 80 (calculated from Worksheet 2). According to Meyer's tables, an 80-year-old "normally stocked" stand has about 5,700 ft³/acre. Actual stocking is only 1,913 cubic feet (Worksheet 1), or about 34 percent of normal. Stocking can be varied by age class to account for past understocking effects. As a first approximation, age classes over 80, which contain stands that were attacked by the budworm when young, were assumed to be less well stocked (30 percent) than 50- to 70-year-old stands (40 percent); the 71- to 80-age class was assumed to be in an intermediate position (Worksheet 2, Fig. 11).

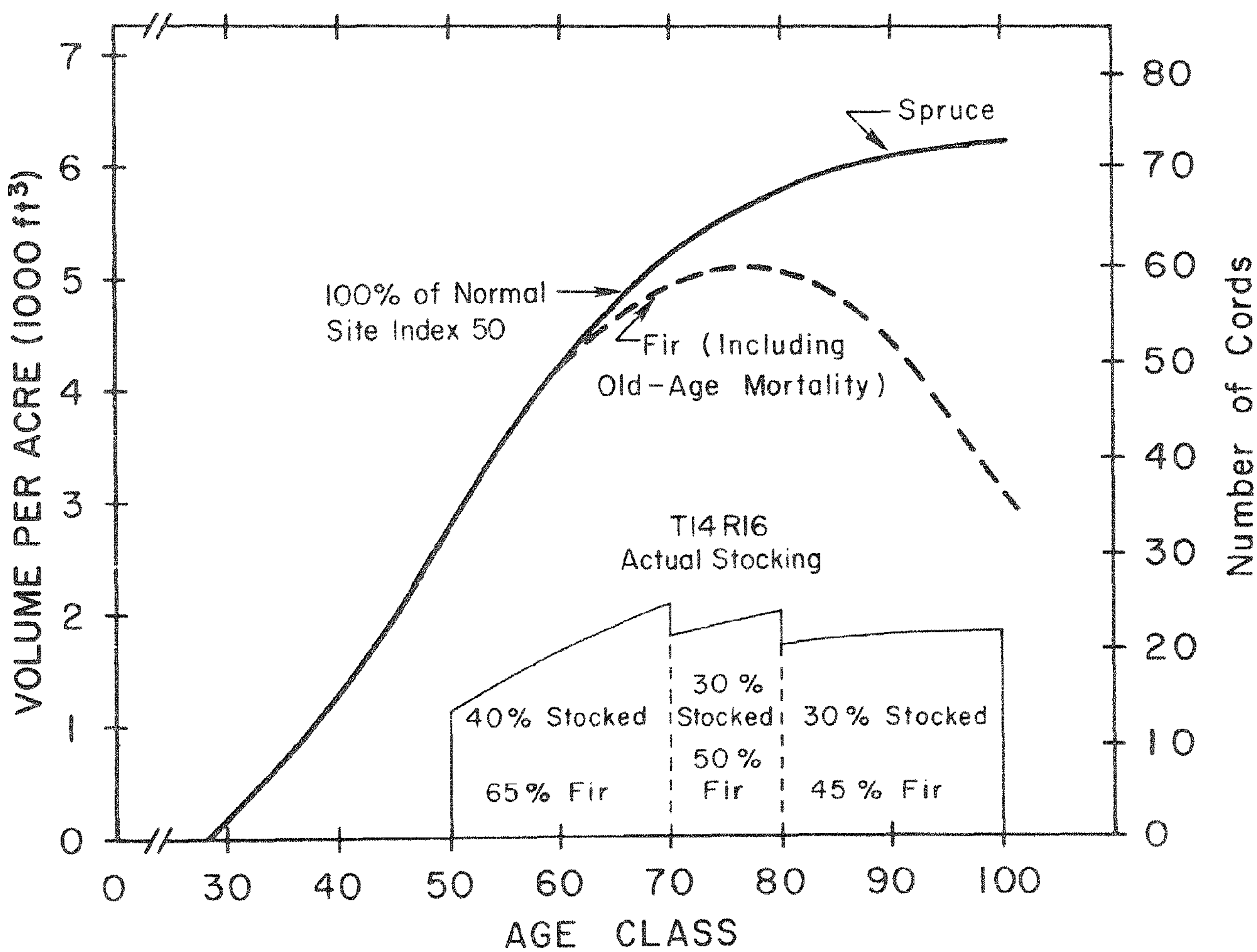


Figure 11.—Actual stocking of T14 R16 compared with Meyer's normal yield table.

### Step 6

Calculate percent fir by age class (Appendix III, 2.12 and 2.13). For age classes with merchantable volume, the percentages should reflect the proportions of fir by volume in each. In the mature softwood stands, (including the residual areas from the older partial cuts), fir averaged about 52 percent of all merchantable volume in the softwood type on T14 R16 (Worksheet 1). One can assume that this percentage applies equally to all age classes, or change the percentages according to a knowledge of the area or more refined data. For example, one might assume that 51- to 70-year-old stands that originated after the last budworm outbreak have a higher proportion of fir than the older age classes which originated after logging. In this example we assumed that 65 percent of the young (51-70) areas were fir, compared with only 45 percent of the stands over 80 years old.

For age classes below 30, areas cannot be assigned in proportion to volume because no merchantable timber is present. Here, the appropriate figure is the percentage of the total volume that will be fir once the stands become merchantable at age 25. Normally, one would obtain these data from regeneration plots. However, the appropriate value is not necessarily the same as the measured percentage in newly established reproduction, since the proportions by species can change by age 30—either through natural development or deliberately from the application of early cultural practices.

### Step 7

Specify the optimum rotation age that would be used if the forest were fully regulated (Appendix III, 2.14). As described in the section on timber harvesting, this parameter is used only to compute an index of how well regulated the forest is at any point during a simulation. It is not used to control simulated harvesting operations; these are governed as described in Step 12. In this case, available markets are mainly for sawtimber, and the landowners would like to regulate their forest on about a 70-year rotation to ensure a steady supply of large-diameter material.

### Step 8

Assign growth rates by species and forest type. If information from remeasured plots is available, the user should specify growth rates directly in cubic feet per acre by species and 20-year age class (Appendix III, 3.1 and 3.2). Unfortunately, no remeasured plots were available for T14 R16, so we chose to predict growth with equations fitted to Meyer's normal yield data (Appendix I) with appropriate adjustments for below normal stocking. In this example, the value chosen theoretically should correspond to the stocking of stands in the 51-70 age classes that have grown essentially undisturbed since 1920. In this case, 40 percent of normal (Site Index 50) was used for both spruce and fir in the softwood type (Appendix III, 3.3), and 30 percent of Site Index 60 for the mixedwood (3.4).

### Step 9

Specify regeneration assumptions. On T14 R16, milacre plots showed a high proportion of fir in the softwood reproduction, and also some mixedwood cutover that was understocked with softwood species. On the basis of these data, we assumed that 30 percent (Appendix III, 4.5) of the mixedwood forest type will be converted to hardwood stands (lost from the spruce-fir resource), and that 10 percent (4.4) of the softwood cutovers would be mixedwood types when they reached merchantable size. Softwood regeneration was set at 80 percent fir (4.3), which means that 80 per cent of the area and volume will be fir when the regenerated area becomes merchantable at age 25. Softwood cutovers generally were well stocked, so no lag (4.1a, 4.2a) period was specified. Eighty percent of the mixedwood cutovers (4.2b) were lagged by 15 years (4.1b) to account for the greater abundance of competing species on these sites. No planting for type conversion from hardwood was planned (4.6).

### Step 10

Determine mortality lag and budworm severity factors. The simulation was begun in 1979; the budworm outbreak began in the early 1970's. However, the simulated budworm outbreak cannot begin before the first year of the simulation, so we started the budworm outbreak in 1979 (Appendix III, 5.1) also. Mortality was just beginning that year on the lands that had been left unprotected since the early 1970s, so this difference is unimportant because we could specify a lag of zero years for fir (6.1b) and 2 years (6.1c) for spruce. This means mortality begins immediately for fir and in 1981 for spruce on the unprotected lands.

It was assumed that virtually all of the fir over age 40 would be killed without protection, with slightly higher survival in the mixedwood type and in stands below age 40. For the 41-70 and 71+ age classes, expected fir survival was set at 5 percent (5.6 b-c) and 20 percent (5.8 b-c) of the total volume for the softwood and mixedwood types, respectively. For fir below age 40, expected survival was set at 40 (5.6a) and 70 percent (5.8a), respectively. For spruce over age 40, 60 (5.7 b-c) and 80 percent (5.9 b-c) of the volume was assumed to survive in the softwood and mixedwood types, respectively. Ninety percent of young spruce was assumed to survive in both types (5.7a and 5.9a).

Growth of unprotected fir and spruce was set at 20 (5.4a) and 50 percent (5.5a), respectively, of their normal rates without a budworm outbreak. Growth was reduced on protected lands to only 50 (5.2a) and 60 percent (5.3a) of the uninfested rates for fir and spruce. Growth reduction was applied for 20 years (until 1999), then eliminated on the premise that the budworm outbreak would end by then.

## Formulating a Management Strategy

### Step 11

Allocate forest protection (Worksheets 2-3). A major use of the model is determining the area that must be protected against budworm-caused tree mortality to meet forest management objectives. Before the model is used, it is necessary to determine the maximum area that physically can be protected with current spray technology. Then, simulation is used to arrive at the actual percentage of this zone that must be protected to sustain a given annual harvest.

The maximum feasible protection zone was developed for T14 R16 from the type map (for stand boundaries) and high-altitude color infrared aerial photography (to assess current tree condition). Blocks as small as 100 acres were drawn with irregular boundaries to include as many high-volume softwood and mixedwood stands as possible, while attempting to exclude other nontarget types. For each stratum, areas in and out of the protection zone were determined by adding the known acreages from the computer stand listings. Borderline stands (those including area both in and out of the protection zone) were planimetered and the areas allocated accordingly.

Of the total protection zone area of 6,037 acres, 512 acres were in nonspruce-fir types, mostly "islands" of hardwood or cedar swamp that were impossible to exclude when drawing block boundaries (Worksheet 3). The remaining 5,525 acres were in one of six strata used to classify the forest structure for simulation. Thus, these acres (92 percent of the total area sprayed) make up the maximum possible area that can be protected in any simulation for this township.

To run the model, the user must specify the percentage of the 1-40, 41-70, 71+ age groups (by forest type and species) to protect (Worksheet 3, columns 5-6).

Because these limits do not necessarily coincide with those of the strata on Worksheet 1, the total protected area must be apportioned to age classes. In this example, we distributed the protected area within each stratum according to its overall age structure. In the fully stocked, mature softwood stands, 4,019 acres fell into the protection zone; this was allocated to age classes from 50 to 100 as shown in Worksheet 2. Similarly, 192 acres of old partial cuts were in the protection zone, which was allocated to the 0-30 and 41-100 age classes. Sixty-five acres of stands clearcut in 1950 also were included. The protected areas in each 10-year age class from each stratum were then added to produce the overall age structure of the protection zone by forest type. Protected areas were summed within the three age groups (Worksheet 2), and the percentage of the total land under protection calculated (Worksheet 3).

For example, the total area protected in the 0-40 stands is 34 + 13 + 85 = 132 acres, which is 13 percent of the 1,024 softwood acres in these age classes.

These percentages can be applied equally to the spruce and fir areas within each age group, or varied to simulate a program targeted on one species. On T14 R16, some of the mature softwood area was excluded from the protection zone because stand composition was nearly pure spruce. These stands tend to be older hybrid red-black spruce, which usually does not require protection. Thus, the 2,913 acres under protection in this age group (Worksheet 3) probably have a higher proportion of fir than the toal area. If the area under protection is 60 percent fir compared with the average of 45 percent for the total area (Worksheet 3), then the percentage of fir to protect in the 71+ age group is found by the formula

$$\frac{(\text{Total protected area})\ (\%\ \text{fir})}{(\text{Total area})\ (\%\ \text{fir})} = \frac{(2913)\ (.60)}{(4943)\ (.45)}$$

$= .79$ percent protected

Enter the derived protection percentages (Worksheet 3, columns 5-6) on the input summary form (Appendix III, 6.1, columns d-o).

## Step 12

Formulate a harvesting strategy. If the simulation covers an historical period to aid in calibrating growth and mortality, harvest levels usually can be obtained from records. Virtually any strategy can be simulated, subject only to the potential limitations imposed by exhausting merchantable inventories. For the analysis of T14 R16, several elements were varied, including the total volume removed, percent fir in the harvest, and the proportion of the cut to be salvaged from dead material.

Initially, the harvesting parameters were set at a best estimate of the current strategy. The annual allowable cut had been 5,000 cords (425,000 ft³) (Appendix III, 7.1b), 70 percent of which was fir. As the inventory is only 52 percent fir, the discrimination against fir (from Figure 6 or calculated from the formula in Appendix I) is 0.18 (Appendix III, 7.1d). Markets limited the percentage of deadwood to 10 percent of the total cut (7.1h). Eighty percent of simulated harvests were concentrated on unprotected lands (7.1f) through 1985 to presalvage as much wood as possible before it was killed by the budworm. In 1986, (7.2a) 90 percent of the cut was allocated back to the protected lands (7.2f) to reduce protection requirements and avoid overcutting the unprotected lands, which become depleted through budworm mortality and presalvage operations. The salvage goal was reduced to 5 percent (7.2h).

# Running a Simulation

## Step 13

Use the interactive program to construct and format the basic data file, calibrate the initial forest structure, and run a simulation. After the input data have been assembled as described in Steps 1 through 12, the interactive program (Appendix II) is used to construct the formatted data file needed to execute the main program. The interactive program queries the user for each item, following the order of the input summary form (Appendix III). This requires no programing expertise, and should be self-explanatory.

When all data have been entered, the user usually runs the interactive program several times to "fine tune" the initial forest characteristics. Stocking levels and age-class data are changed heuristically until the inventory of the simulated forest agrees with the actual values. The interactive program is designed so that any selected input parameters can be changed quickly and efficiently without needless repetition. Inconsistencies in the original data may become apparent, and judgment is needed when changes must be made. With experience, users should be able to arrive at close agreement after only a few iterations.

# Exploration of Scenarios

Once the initial forest structure is calibrated, further modifications to the input data file usually are limited to changes in management strategy. At this stage, typical uses would be to derive the minimum protection zone required to ensure a particular harvest level, or to determine the maximum sustainable harvest possible under a fixed level of protection.

It is important to recognize that, unlike certain harvest scheduling models which give "optimum" solutions, this model is not designed to give users "the answer" in one run. Each simulation is a unique result of the particular management strategy interacting with the specified forest dynamics, both of which are under the user's control. An adequate, thorough analysis requires many runs in which critical assumptions are varied to see if they affect the outcomes. Many sources of uncertainty merit serious scrutiny, including the accuracy of the user's conception of the initial forest structure; whether the key forest dynamics (growth, budworm damage, regeneration) develop as expected; and whether the simulated management intervention (harvesting, protection, and silviculture) can be implemented as planned.

Through repeated simulations, users begin to appreciate that a wide range of "futures" is possible. Since the future can never be rendered certain, the understanding of these complex and dynamic interactions gained in the analysis probably is more valuable to the manager than any single detail of the output.

## Literature Cited


Baskerville, G. L. **Deterioration and replacement in two overmature forest stands.** Publ. No. 1125. Ottawa: Canada Department of Forestry; 1965. 16 p.

Baskerville, G. L. **Spruce budworm: super silviculturist.** Forestry Chronicle 51: 138-140; 1975.

Baskerville, G. L.; MacLean, D. A. **Budworm-caused mortality and 20-year recovery in immature balsam fir stands.** Inf. Rep. M-X-102. Fredericton, N. B.: Maritimes Forest Research Centre; 1979. 23 p.

Belyea, R. M. **Death and deterioration of balsam fir weakened by spruce budworm defoliation in Ontario.** Journal of Forestry. 50:720-738; 1952.

Blais, J. R. **The vulnerability of balsam fir to spruce budworm attack in northwestern Ontario, with special reference to the physiological age of the tree.** Forestry Chronicle. 34: 405-422; 1958.

Dimond, J. B.; Seymour, R. S.; Mott, D. G. **Planning insecticide application and timber harvesting in a spruce budworm epidemic.** Agriculture Handbook 618. Washington, DC: U.S. Department of Agriculture; 1984.

Field, D. B.; Shottafer, J. E. **Utilizing spruce budworm-damaged timber in Maine—a problem analysis.** CFRU Inf. Rep. 3. Orono, ME: University of Maine, School of Forestry Resources; 1979. 18 p.

Gevorkiantz, S. R.; Olsen, L. P. **Growth and yield of upland balsam fir in the Lake States.** Stn. Pap. 22. St. Paul, MN: U.S. Department of Agriculture, Forest Service, Lake States Forest Experiment Station; 1950. 24 p.

Ghent, A. W.; Fraser, D. A.; Thomas J. B. **Studies of regeneration in forest stands devastated by the spruce budworm.** I. Evidence of trends in forest succession during the first decade following budworm devastation. Forest Science. 3: 184-208; 1957.

Kleinschmidt, S. M.; Baskerville, G. L.; Solomon, D. S. **Reduction of volume increment in fir-spruce stands due to defoliation by spruce budworm.** CANUSA Misc. Publ. Fredericton, NB: University of New Brunswick; 1980. 37 p.

MacLean, D. A. **Vulnerability of fir-spruce stands during uncontrolled spruce budworm outbreaks: a review and discussion.** Forestry Chronicle. 56: 213-221; 1980.

Meyer, W. H. **Yields of second-growth spruce and fir in the Northeast.** Tech. Bull. 142. Washington, DC: U.S. Department of Agriculture; 1929. 52 p.

Mott, D. G. **The consequences of applying no control to epidemic spruce budworm.** In: Proceedings of a symposium on the spruce budworm; 1974 November 11-14; Alexandria, VA. Misc. Publ. No. 1327. Washington, DC: U.S. Department of Agriculture, Forest Service; 1976; 67-72.

Mott, D. G. **Spruce budworm protection managment in Maine.** Maine Forest Review. 13: 26-33; 1980.

Rumpf, T. A.; Irland, L. C.; Blackmer, S. D. **Spruce budworm policy in Maine: tradition, conflict and adaptation.** Journal of Forestry. 80: 708-711, 720; 1982.

Seegrist, D. W.; Arner, S. L. **The volume of spruce and fir mortality in 1976-78 due to the spruce budworm outbreak in Maine.** Res. Pap. NE-491. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1982. 3 p.

Sewall Company. **Spruce-fir wood supply/demand analysis.** Final report. Augusta, ME: Maine Department of Conservation; 1983. 94 p.

Seymour, R. S. **Vulnerability to spruce budworm damage and 100-year development of mixed red spruce-fir stands in north central Maine.** New Haven, CT: Yale University; 1980. 160 p. Ph.D. Dissertation.

Westveld, M. **Reproduction on the pulpwood lands in the Northeast.** Bull. 223. Washington, DC: U.S. Department of Agriculture; 1931. 52 p.

Westveld, M. **Ecology and silviculture of the spruce-fir forests of eastern North America.** Journal of Forestry. 51: 422-430; 1953.


## Acknowledgments


Research and development of the Green Woods Model was supported by the Canada-United States Spruce Budworms Program (CANUSA) and the USDA Forest Service, Northeastern Area, State and Private Forestry, both of the USDA Forest Service, through cooperative agreement 42-351 with the College of Forest Resources, University of Maine at Orono. We gratefully acknowledge the contributions of Stephen Fairweather and Robert Wright, Great Northern Paper Co., Roger Greene, St. Regis Paper Co., and Michael Dann, Seven Islands Land Co., whose cooperation and applications improved the model significantly. We sincerely appreciate the critical review of the manuscript by Dr. Gordon L. Baskerville, University of New Brunswick.

#### Step 12

Formulate a harvesting strategy. If the simulation covers an historical period to aid in calibrating growth and mortality, harvest levels usually can be obtained from records. Virtually any strategy can be simulated, subject only to the potential limitations imposed by exhausting merchantable inventories. For the analysis of T14 R16, several elements were varied, including the total volume removed, percent fir in the harvest, and the proportion of the cut to be salvaged from dead material.

Initially, the harvesting parameters were set at a best estimate of the current strategy. The annual allowable cut had been 5,000 cords (425,000 $ft^3$) (Appendix III, 7.1b), 70 percent of which was fir. As the inventory is only 52 percent fir, the discrimination against fir (from Figure 6 or calculated from the formula in Appendix I) is 0.18 (Appendix III, 7.1d). Markets limited the percentage of deadwood to 10 percent of the total cut (7.1h). Eighty percent of simulated harvests were concentrated on unprotected lands (7.1f) through 1985 to presalvage as much wood as possible before it was killed by the budworm. In 1986, (7.2a) 90 percent of the cut was allocated back to the protected lands (7.2f) to reduce protection requirements and avoid overcutting the unprotected lands, which become depleted through budworm mortality and presalvage operations. The salvage goal was reduced to 5 percent (7.2h).

### Running a Simulation

#### Step 13

Use the interactive program to construct and format the basic data file, calibrate the initial forest structure, and run a simulation. After the input data have been assembled as described in Steps 1 through 12, the interactive program (Appendix II) is used to construct the formatted data file needed to execute the main program. The interactive program queries the user for each item, following the order of the input summary form (Appendix III). This requires no programing expertise, and should be self-explanatory.

When all data have been entered, the user usually runs the interactive program several times to "fine tune" the initial forest characteristics. Stocking levels and age-class data are changed heuristically until the inventory of the simulated forest agrees with the actual values. The interactive program is designed so that any selected input parameters can be changed quickly and efficiently without needless repetition. Inconsistencies in the original data may become apparent, and judgment is needed when changes must be made. With experience, users should be able to arrive at close agreement after only a few iterations.

### Exploration of Scenarios

Once the initial forest structure is calibrated, further modifications to the input data file usually are limited to changes in management strategy. At this stage, typical uses would be to derive the minimum protection zone required to ensure a particular harvest level, or to determine the maximum sustainable harvest possible under a fixed level of protection.

It is important to recognize that, unlike certain harvest scheduling models which give "optimum" solutions, this model is not designed to give users "the answer" in one run. Each simulation is a unique result of the particular management strategy interacting with the specified forest dynamics, both of which are under the user's control. An adequate, thorough analysis requires many runs in which critical assumptions are varied to see if they affect the outcomes. Many sources of uncertainty merit serious scrutiny, including the accuracy of the user's conception of the initial forest structure; whether the key forest dynamics (growth, budworm damage, regeneration) develop as expected; and whether the simulated management intervention (harvesting, protection, and silviculture) can be implemented as planned.

Through repeated simulations, users begin to appreciate that a wide range of "futures" is possible. Since the future can never be rendered certain, the understanding of these complex and dynamic interactions gained in the analysis probably is more valuable to the manager than any single detail of the output.

### Species Discrimination Function for Simulated Harvesting

$$(5)\ \%CUT = \%INV + [\%INV \times (1 - \%INV)]^{x}$$

where $x = \text{Log}_e(\text{DISCRIM}) / -1.3863$

DISCRIM = harvest discrimination parameter, defined as the difference between %CUT and %INV when %INV = 0.5 (i.e., the "extra" proportion of fir in the cut, above that in the inventory, when the inventory is 50:50 spruce-fir).

%CUT = proportion of fir in harvest (range = 0 - 1.0)

%INV = proportion of fir (by volume) in harvestable age classes

If harvest discrimination against *spruce* is specified, the "+" sign becomes a minus.

# Appendix II

## Programing Considerations

### Interactive Program for Constructing and Modifying Input Data Files

Potential users are often prevented from applying large simulation models because they lack programing expertise or are not conversant in the command language used to create and edit data files or run programs at their particular installation. To overcome these obstacles, an interactive program was developed that allows computer novices to use the model as readily as experts. The interactive program is essentially a customized editor which prompts the user in plain English for instructions or data inputs. Data are checked for errors and to see if they lie within acceptable ranges, and error messages are produced as appropriate. It also initiates simulations (executes the model) and produces tabular and graphical output of the results.

Three levels of editing are available, depending on the needs of the user and his familiarity with the model. The INITIAL *format* is for first-time users or for constructing an input data file from scratch. This option includes detailed prompts for information which should be virtually self-explanatory to any user with a general understanding of the model structure. The order of data input follows exactly the INPUT SUMMARY FORM (APPENDIX III); if the user can complete this form, he should have no trouble responding to the queries of the INITIAL format. The GENERAL format is designed primarily for inexperienced users, and omits much of the detailed descriptions which become repetitive for users at this level of understanding. The SPECIFIC format is designed to allow minor changes in the input data file (such as a simple change in one aspect of the harvesting strategy) to be made efficiently and without needless repetition of prompts.

### Software and Operating Systems

The main simulation program is written in PLI, and will compile under the IBM PLI/F compiler. The object deck requires at least 512K bytes of core to load and execute. Due to its large size, the program generally is run in batch mode. The interactive data entry program is written in WATFIV and is executed by an EXEC file.

Two auxiliary programs are also available to summarize simulation results in a more usable form. The first gives tabular listings of the output; it is written in FORTRAN and compiles under the IBM FORTG compiler. The second produces a graphical output and is written in the command language of the Statistical Analysis System (SAS).

All programs are presently operational at the University of Maine at Orono computing center, which uses IBM's Conversational Monitoring System (CMS). With little modification, the complete package could be installed on any IBM system that supports PLI, FORTRAN, WATFIV, SAS, and an EXEC facility. The model itself (without peripherals) can be run under any system that supports PLI and has sufficient memory. Programing expertise and experience with the operating system at the particular installation would be needed initially to make the package operational. At this stage, users probably would "customize" the package to produce the particular kind of output desired. Once the package is installed and the system linkages debugged, anyone who can use a terminal, with or without programing ability, should be able to carry out a simulation successfully.

# Appendix III

Summary Form for Input Variables

1. SIMULATION PARAMETERS

1.1 TITLE: ____________________________________________

1.2 SIMULATION PERIOD: from _____ to _____ LENGTH OF SIMULATION (YEARS): _____

1.3 PRINT ANNUAL REPORT? _____

1.4 PRINT AGE-CLASS INVENTORY TABLES EVERY _____ YEARS

1.5 PROCEDURE TO INITIALIZE FOREST: NORMAL YIELD FUNCTION _____ OR ACTUAL VOLUMES PER ACRE _____

1.6 PROCEDURE TO GROW FOREST: GROWTH FUNCTION _____ OR ACTUAL GROWTH RATES _____

1.7 APPLY OLD-AGE MORTALITY FUNCTION FOR FIR? _____

2. FOREST CHARACTERISTICS

FOREST LAND AREA

2.1 SOFTWOOD TYPE: __________ thousand acres

2.2 MIXEDWOOD TYPE: __________ thousand acres

AGE-CLASS DISTRIBUTION (% OF TOTAL AREA BY 10-YEAR AGE CLASSES)

| | 0-10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 130 | 140 | 150 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.3 SOFTWOOD | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| 2.4 MIXEDWOOD | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |

IF USING NORMAL-STOCKING OPTION, SKIP TO 2.10

VOLUME PER ACRE (MERCHANTABLE CUBIC FEET) BY SPECIES, FOREST TYPE AND 10-YEAR AGE CLASS:

| | 0-10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 130 | 140 | 150 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.5 FIR, SW | | | | | | | | | | | | | | | |
| 2.6 SPRUCE, SW | | | | | | | | | | | | | | | |
| 2.7 FIR, MW | | | | | | | | | | | | | | | |
| 2.8 SPRUCE, MW | | | | | | | | | | | | | | | |

PROPORTION FIR IN UNMERCHANTABLE (0-10, 11-20, 21-30) AGE CLASSES

| | 0-10 | 11-20 | 21-30 |
|---|---|---|---|
| 2.9 | | | |

SKIP TO 2.14

NORMAL STOCKING BY FOREST TYPE AND 10-YEAR AGE CLASS (PROPORTION OF YIELD FUNCTION):

| | 0-10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 130 | 140 | 150 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.10 SOFTWOOD | | | | | | | | | | | | | | | |
| 2.11 MIXEDWOOD | | | | | | | | | | | | | | | |

PROPORTION FIR BY FOREST TYPE AND 10-YEAR AGE CLASS:

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.12 SOFTWOOD | | | | | | | | | | | | | | | |
| 2.13 SOFTWOOD | | | | | | | | | | | | | | | |

2.14 OPTIMUM ROTATIION AGE: ____

## 3. FOREST GROWTH RATES

IF GROWTH FUNCTION OPTION WAS SPECIFIED, SKIP TO 3.3

NET GROWTH PER ACRE BY SPECIES AND 20-YEAR AGE CLASSES:

| | 25-30 | 31-50 | 51-70 | 71-90 | 91+ |
|---|---|---|---|---|---|
| 3.1 FIR | ____ | ____ | ____ | ____ | ____ |
| 3.2 SPRUCE | ____ | ____ | ____ | ____ | ____ |

PROPORTION OF FUNCTION-CALCULATED OR USER-SPECIFIED GROWTH TO APPLY BY SPECIES AND FOREST TYPE:

3.3 SOFTWOOD TYPE FIR: ____ SPRUCE: ____

3.4 MIXEDWOOD TYPE FIR: ____ SPRUCE: ____

## 4. FOREST REGENERATION RATES

4.1 REGENERATION LAG (YEARS) FOR SOFTWOOD (a) ____ MIXEDWOOD (b) ____

4.2 PROPORTION OF REGENERATED AREA LAGGED: SOFTWOOD (a) ____ MIXEDWOOD (b) ____

4.3 PROPORTION OF FIR IN SOFTWOOD REGENERATION ____

4.4 PROPORTION OF HARVESTED SOFTWOOD ACRES REGENERATING TO MIXEDWOOD ____

4.5 PROPORTION OF HARVESTED MIXEDWOOD ACRES REGENERATING TO HARDWOOD ____

4.6 ANNUAL AREA OF HARDWOOD ADDED TO SOFTWOOD SPRUCE ____ thousand acres

## 5. BUDWORM EFFECTS

5.1 YEAR TO BEGIN BUDWORM OUTBREAK: ____

GROWTH REDUCTION RATES BY SPECIES AND PROTECTION STATUS:

| | GROWTH LOST (% OF PRE-OUTBREAK) (a) | DURATION (YEARS) (b) |
|---|---|---|
| 5.2 PROTECTED FIR | ____ | ____ |
| 5.3 PROTECTED SPRUCE | ____ | ____ |
| 5.4 UNPROTECTED FIR | ____ | ____ |
| 5.5 UNPROTECTED SPRUCE | ____ | ____ |

SURVIVAL RATES (PROPORTION OF INITIAL VOLUME) IN UNPROTECTED AREAS, BY BROAD AGE CLASS:

| | 0-40 (a) | 41-70 (b) | 71-150 (c) |
|---|---|---|---|
| 5.6 SOFTWOOD FIR | ____ | ____ | ____ |
| 5.7 SOFTWOOD SPRUCE | ____ | ____ | ____ |
| 5.8 MIXEDWOOD FIR | ____ | ____ | ____ |
| 5.9 MIXEDWOOD SPRUCE | ____ | ____ | ____ |

## 6. FOREST PROTECTION STRATEGIES

| | YEAR TO BEGIN | MORTALITY LAG (YRS) | | PROPORTION OF AREA WHERE NO MORTALITY WILL OCCUR BY FOREST TYPE, SPECIES, AND BROAD AGE CLASS: SOFTWOOD FIR | | | SOFTWOOD SPRUCE | | | MIXEDWOOD FIR | | | MIXEDWOOD SPRUCE | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | FIR | SPRUCE | 0-40 | 41-70 | 71+ | 0-40 | 41-70 | 71+ | 0-40 | 41-70 | 71+ | 0-40 | 41-70 | 71+ |
| | (a) | (b) | (c) | (d) | (e) | (f) | (g) | (h) | (i) | (j) | (k) | (l) | (m) | (n) | (o) |
| 6.1 | | | | | | | | | | | | | | | |
| 6.2 | | | | | | | | | | | | | | | |
| 6.3 | | | | | | | | | | | | | | | |
| 6.4 | | | | | | | | | | | | | | | |
| 6.5 | | | | | | | | | | | | | | | |
| 6.6 | | | | | | | | | | | | | | | |

## 7. HARVESTING STRATEGIES

7.0 YOUNGEST HARVESTABLE AGE, BY SPECIES: FIR ____ SPRUCE ______

| | | | SPECIES DISCRIMINATION | | PROTECTED LAND ALLOCATION | | CUT FROM | DEAD WOOD IN |
|---|---|---|---|---|---|---|---|---|
| | YEAR (a) | HARVEST VOLUME (M $FT^3$) (b) | CODE (c) | % (d) | CODE (e) | % (f) | OLDEST (%) (g) | UNPROT. CUT (%) (h) |
| 7.1 | | | | | | | | |
| 7.2 | | | | | | | | |
| 7.3 | | | | | | | | |
| 7.4 | | | | | | | | |
| 7.5 | | | | | | | | |
| 7.6 | | | | | | | | |
| 7.7 | | | | | | | | |
| 7.8 | | | | | | | | |

(NOTE: UP TO 30 HARVEST STRATEGIES CAN BE SPECIFIED SIMPLY BY REPEATING THESE ENTRIES.)

SPECIES DISCRIMINATION CODES:

0 = NO DISCRIMINATION

1 = DISCRIMINATION AGAINST FIR

2 = DISCRIMINATION AGAINST SPRUCE

PROTECTED LANDS ALLOCATION CODES:

0 = NO DISCRIMINATION (HARVEST BOTH LAND TYPES IN PROPORTION TO THEIR OCCURRENCE)

1 = CUT SPECIFIED PROPORTION FROM UNPROTECTED LANDS

2 = CUT SPECIFIED PROPORTION FROM PROTECTED LANDS

## Appendix IV

WORKSHEET 1. SUMMARY OF FOREST INVENTORY INFORMATION NEEDED TO DERIVE MODEL INPUT DATA

| STRATUM | AREA | RANGE IN AGE | VOLUME/ACRE ($FT^3$) FIR | SPRUCE | TOTAL | % FIR | AVERAGE AGE | PERCENT OF NORMAL STOCKING |
|---|---|---|---|---|---|---|---|---|
| 1 Fully stocked mature softwood | 6329 | 50-100 | 1030 | 883 | 1913 | 54 | 80 | 1913/5700 = .34 |
| 2 Softwood stands partially cut since 1950 | 988 < 347 / 641 | 0-30 regn. / 60-100 overstory | 476 | 766 | 1242 (65%) | 38 | | |
| 3 Softwood stands clearcut since 1950 | 677 | 0-30 | 0 | 0 | 0 | regen. data 80 | — | N/A |
| 4 | | | | | | | | |

TOTAL, SOFTWOOD TYPE 7,993

| STRATUM | AREA | RANGE IN AGE | FIR | SPRUCE | TOTAL | % FIR | AVERAGE AGE | PERCENT OF NORMAL STOCKING |
|---|---|---|---|---|---|---|---|---|
| 1 Fully stocked, mature mixedwood | 1942 | 50-100 | 1172 | 599 | 1771 | 66 | 80 | 1771/7280 = .24 |
| 2 Mixedwood partially cut since 1950 | 721 < 324 / 397 | 0-30 regen. / 40-100 overstory | 764 | 213 | 977 (55%) | 78 | | |
| 3 Mixedwood clearcut since 1950 | 591 | 0-30 | 0 | 0 | 0 | regen 80 | — | N/A |
| 4 | | | | | | | | |

TOTAL, MIXEDWOOD TYPE 3254

TOTAL, ENTIRE FOREST 11,247

WORKSHEET 2. DERIVATION OF TOTAL AND PROTECTED AREAS, PERCENT FIR, AND PERCENT STOCKING, BY 10-YEAR AGE CLASS

FOREST: 774 R16 FOREST TYPE: SOFTWOOD

| AGE CLASS | STRATUM 1 mature, fully stocked | | | STRATUM 2 recent partial cuts | | | STRATUM 3 recent clearcuts | | | ~~STRATUM~~ TOTALS ALL STRATA | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | TOTAL AREA | PROT. AREA | % | TOTAL AREA | PROT. AREA | % | TOTAL AREA | PROT. AREA | % | TOTAL AREA | PROT. AREA | % FIR |
| 0 - 10 | | | | 50 | 174 | 34 | 85 | 574 | 0 | 09 ~~09~~ | 749 | 34 | 80 |
| 11 - 20 | | | | 20 | 69 | 13 | 0 | 0 | 0 | 01 | 69 | 13 | 80 |
| 21 - 30 | | | | 30 | 104 | 20 | 15 | 102 | 65 | 03 | 206 | 85 | 80 |
| 31 - 40 | | | | Subtotal | 347 | | | | | — | 0 | — | — |
| 41 - 50 | | | | | | | | | | — | 0 | — | — |
| 51 - 60 | 05 | 316 | 201 | | | | | | | 04 | 316 | 201 | 65 |
| 61 - 70 | 25 | 1582 | 1005 | 20 | 128 | 25 | | | | 22 | 1710 | 1030 | 65 |
| 71 - 80 | 25 | 1582 | 1005 | 30 | 192 | 37 | | | | 22 | 1774 | 1042 | 50 |
| 81 - 90 | 15 | 949 | 603 | 20 | 129 | 25 | | | | 13 | 1078 | 628 | 45 |
| 91 -100 | 30 | 1899 | 1206 | 30 | 192 | 37 | | | | 26 | 2091 | 1243 | 45 |
| 100+ | | | | subtotal | 641 | | | | | | | | |
| TOTAL | 100 | 6,329 | 4,019 | 100 | 988 | 192 | 100 | 677 | 65 | 100 | 7993 | 4276 | |

WORKSHEET 3. DERIVATION OF TARGETED PROTECTION STRATEGY BY FOREST TYPE, AGE CLASS AND SPECIES

FOREST: T14 R16

| FOREST TYPE AND AGE CLASS | TOTAL AREA | | PROTECTED AREA | | PERCENT PROTECTED | |
|---|---|---|---|---|---|---|
| | ACRES (1) | % FIR (2) | ACRES (3) | % FIR (4) | FIR (5) | SPRUCE (6) |
| SOFTWOOD | | | | | | |
| 0 - 40 | 1024 | 80 | 132 | 80 | 13 | 13 |
| 41 - 70 | 2026 | 65 | 1231 | 65 | 61 | 61 |
| 71+ | 4943 | 45 | 2913 | 60 | 79 | 43 |
| TOTAL | 7993 | | 4276 | | | |
| MIXEDWOOD | | | | | | |
| 0 - 40 | 915 | 80 | 46 | 80 | 05 | 05 |
| 41 - 70 | 625 | 70 | 30 | 70 | 49 | 49 |
| 71+ | 1714 | 70 | 896 | 70 | 52 | 52 |
| TOTAL | 3254 | | | | | |
| TOTAL, SPRUCE-FIR RESOURCE | 11,247 | | 5525 | | | |
| TOTAL, ENTIRE FOREST | 14,500 | | 6037 | | | |

(1), (2) and (3) are derived by adding areas in ten-year age classes from WORKSHEET 2.

(4) is specified to give desired level of targeted protection.

$$(5) = \frac{(3) \times (4)}{(1) \times (2)} \qquad (6) = \frac{(3) \times [1.0 - (4)]}{(1) \times [1.0 - (2)]}$$