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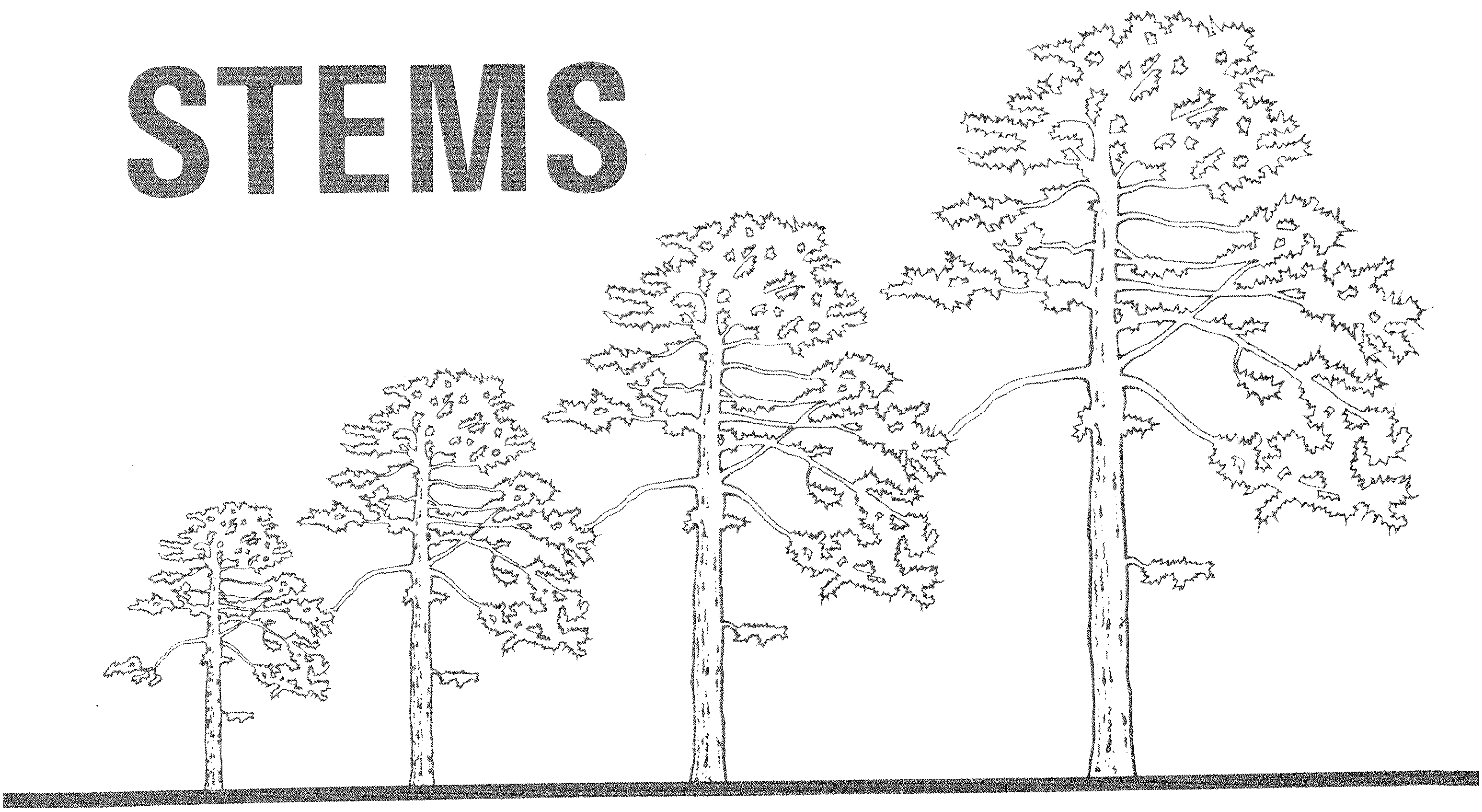
A Description of STEMS

The Stand and Tree Evaluation and Modeling System

David W. Belcher, Margaret R. Holdaway, and Gary J. Brand

STEMS



North Central Forest Experiment Station
Forest Service—U.S. Department of Agriculture
1992 Folwell Avenue
St. Paul, Minnesota 55108
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FOREWORD

In 1975, research was begun at the North Central Forest Experiment Station to develop a system that would update, project, and analyze forest resource information in the North Central Region. This comprehensive evaluation system, designed to analyze all forest resources and their uses as an integrated system, is known as FREP (Forest Resources Evaluation Program).

STEMS (Stand and Tree Evaluation and Modeling System) is the tree growth projection component of FREP. This component has also been known as TRES, FREP, and FREP78. Today's STEMS is the product of a team of researchers at the North Central Station; the development of STEMS continutes.

This publication is one of three designed to acquaint you with different aspects of STEMS. A Description of STEMS, the User's Guide to STEMS, and A Programmer's Guide for STEMS make up the set.

CONTENTS

A DESCRIPTION OF STEMS— THE STAND AND TREE EVALUATION AND MODELING SYSTEM

David M. Belcher, *Biometrician*,
Margaret R. Holdaway, *Mathematical Statistician*,
and **Gary J. Brand**, *Mensurationist*

Long range planning is an essential part of all forest resource management. Prudent management requires accurate estimates of both current resource levels and the expected resource changes from implementing various management alternatives. Such information is required by law at State and Federal levels. For private industry, the commitment of capital requires estimates of present and future resource levels that are at least as accurate as those mandated by legislation.

Even with our rapidly expanding expertise in inventory procedures, our estimates of present and future resource levels have numerous voids. Sampling techniques capable of providing accurate estimates of current forest resource levels are available (Cochran 1977, Prodan 1968, Husch *et al.* 1972) but it is seldom practical to reinventory the forest every time current information is needed. Furthermore, resource inventories furnish no indication of future changes that could result from implementing various management alternatives. Therefore, a desirable goal is a resource management system that will add a dynamic dimension to the inventory process through simulation.

Most work in the area of forest resource simulation has been concentrated on timber projections and many excellent growth and yield models have been developed (Fries 1974, Fries *et al.* 1978). However, most of these models have been restricted to one or a few species groups in a relatively narrow geographic region. This segmented wealth of knowledge is of only limited value to the forest manager who must deal with all species and all forest resources, often over a broad geographical expanse. In recent years more emphasis has been placed on constructing comprehensive simulators that can better portray the dynamics of a diverse resource base. Still, the economically unimportant species, mixed stands, and forest resources other than timber have received little attention.

As a result of these many needs, the development of the Forest Resources Evaluation Program (FREP) was undertaken by the North Central Forest Experiment Station, USDA Forest Service, in 1975. The ultimate goal of the FREP project is to achieve the ability to simulate changes in all major forest resources. The value of such a projection system is twofold. First, it provides a mechanism for the detailed **update** of previously inventoried resources to estimate current resource levels. Second, it allows the detailed **projection** of future resource levels based on known or estimated current levels. Projections with and without silvicultural treatments can be made to provide the basis for resource assessment. Updates and projections for large geographic regions and a diversity of resource conditions can be made.

The first forest resource chosen was timber because of the wealth of information available in the literature and because a large amount of data on tree growth was readily accessible (Leary 1979).

Information about FREP and earlier versions of the tree growth projection system (TRES and FREP78) have been previously published (Buchman 1978, Lundgren 1978, Lundgren and Essex 1978, USDA Forest Service 1979, Hahn *et al.* 1979, Smith and Raile 1979). A short version of STEMS has also been produced (Brand 1981a).

This paper describes the computer program STEMS (Stand and Tree Evaluation and Modeling System), the current version of the tree growth projection system. It presents the program structure, discusses the growth model components, the management subsystem, and the regeneration subsystem. Some preliminary results of model testing are also presented and an example is discussed.

STRUCTURE OF THE STEMS SYSTEM

STEMS is a system of computer programs that projects the growth of individual trees in stands. Based on biological principles of forest growth, STEMS offers a flexible, generalized approach to simulating the change of forest trees in stands. Coefficients for its generalized diameter growth and mortality functions have been developed from more than 2,500 permanent remeasured plots for all the major tree species in the Lake States region of the United States.

STEMS is an individual-tree, distance-independent model that can provide much detail about trees and stands. Because each tree is projected individually (as a member of a competing community of trees), the system offers the user the opportunity to tailor output and silvicultural treatment subroutines to meet his specific objectives. User control of management options and output summaries further serves to make STEMS suitable to a variety of user needs. Changes for a single stand may be monitored in great detail and whole forest inventories may be projected.

STEMS consists of two FORTRAN programs—TGPS and TABL (fig. 1). The program TGPS (Tree Growth Projection System) "grows" stands of forest trees by simulating the birth, growth, harvest, and death of individual trees within a stand. Projection equations predict annual diameter growth of the tree, probability of mortality, and crown ratio. TGPS applies management action (removals) to the stands according to management guides developed for Lake States conditions (Brand 1979, 1981b). Regeneration of stands removed by management action is also provided. TGPS produces a standard output file of initial and updated tree lists for later summarization by TABL (TABLes) or other programs.

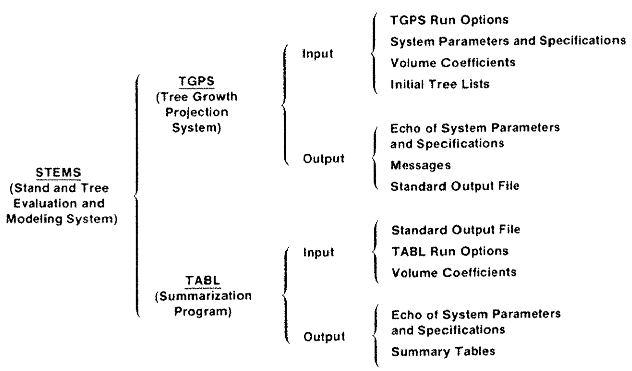

Figure 1.—*Organization of the STEMS system.*

Program TABL is available for summarization c the standard output file by species group and usei specified diameter class. The summary tables pre sent the components of growth in terms of numbe of trees per acre and basal area with optional volumes

TGPS Program

Program TGPS consists of a series of subroutines that perform the required input, processing, and output (fig. 2). The first action of the program is to set up the projection environment by reading the run options, the system parameters and specifications, and the volume equation coefficients with subroutines SETRUN, SETSYS, and SETVOL, respectively. These subroutines and all others presented in this discussion are fully detailed by Belcher (1981).

The remaining subroutines compose the Plot Processor Loop. This loop is executed once for each plot on the input file or for a lesser number of plots if the appropriate run option is used. The first action of the Plot Processor Loop is to read an initial tree list with Subroutine READ. Next, Subroutine TESTIT examines the list to search for conditions likely to produce undesirable results further along in the program. Informative messages are printed to describe any problems that exist or corrective measures that have been taken. The detail of these informative messages is controlled with another run option.

Next Subroutine WRITER is called. This subroutine writes three types of information to the Standard Output File (discussed in a later section). The first is plot-specific information that does not change during the projection period (e.g., property name, site index, etc.). The second is the current tree list, and the third is a trailer record that indicates all output is complete for this plot. At this point within the Plot Processor Loop only the plot-specific information is written.

Subroutines SETSI computes site index by species group. This technique is based on the work by Carmean and Vasilevsky (1971) and Carmean (1979).

Subroutine COVTYP sets the cover type for the plot by examining the current basal area of each species group. This first call to COVTYP computes the cover type for the initial tree list.

Subroutine WRITER is called next to write the initial tree list and stand conditions to the Standard Output File. Note that no projection has yet been done. The initial tree list written here is the same one entered with READ and is included in the output file for summarization purposes.

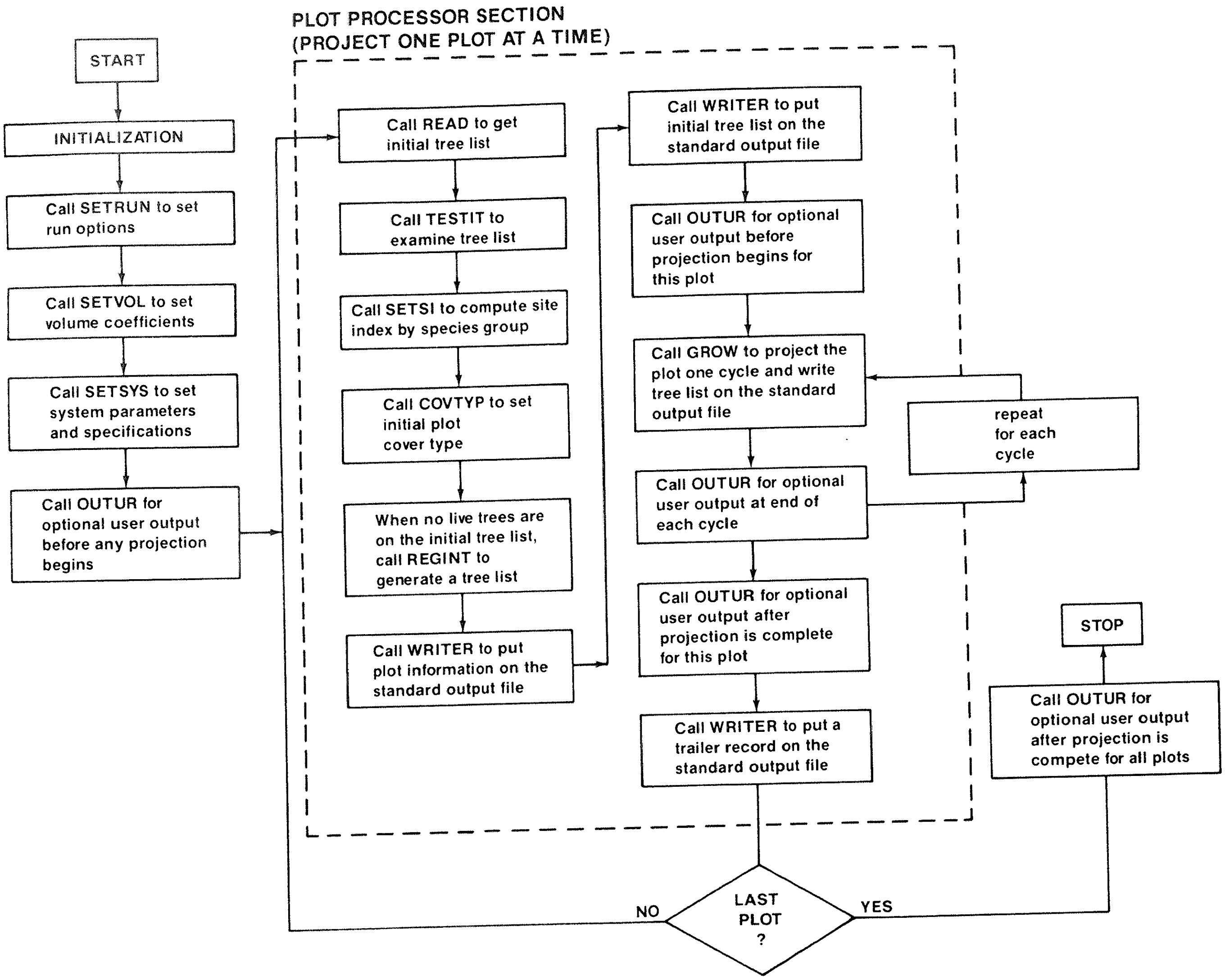

Figure 2.—*Organization of TGPS, the tree growth processor.*

At this point, TGPS enters the Growth and Management Section, which is executed once for each of the cycles requested in the run options. The main feature of this section is a call to Subroutine GROW that "grows" the plot for one cycle by applying a sequence of 1-year projections of growth and mortality. If management is desired, it is performed at the requested point within the cycle by calls to Subroutine MANAGE. If regeneration is required, it is applied at the appropriate point. The projected tree list is written to the Standard Output File by Subroutine WRITER from within GROW.

When the Growth and Management Loop has completed all of its cycles, the projection of the current plot is complete. WRITER is again called to write a record on the Standard Output File to indicate the end of the plot projection. This also signals the end of the Plot Processor Loop and control returns to READ to enter the next plot to be projected.

When all the plots to be projected are complete, a final call to WRITER is made to print the format used for the Standard Output File. This is the format to be followed if the user will summarize the Standard Output File tree lists with his own summarization program.

Throughout the program, TGPS provides calls to Subroutine OUTUR. This subroutine consists only of the common block and RETURN statement. Use of OUTUR is optional but is included as a place for inserting user-written code to do summarization, output, or any further processing.

TABL Program

Program TABL (fig. 3) summarizes the standard output file produced by TGPS. The program first reads the TABL run options, system specifications, and volume equation coefficients. Then the Plot Processor Loop is entered and the plot specific information is read for the first plot. Next a tree list is read, and subroutine SETIT organizes calls to subroutine SUMARY to compute the current plot conditions and to subroutine TABLE to print a plot summary. The read-summarize-print loop is repeated until all information is printed for the current plot. Then the next plot on the standard output file from TGPS is processed.

When all plots have been processed, summaries of all plots combined may be printed. The types of tables printed and the details of each are controlled by TABL run options (for more detail on the summarization and tabling process see Belcher 1981).

GROWTH MODEL COMPONENTS

The STEMS tree growth simulation model consists of four components: (1) a function that estimates the potential annual diameter growth of an individual tree, (2) a modifier function to reduce the potential growth because forest-grown trees may be competing for limited resources and therefore not reach their potential growth, (3) a mortality function, and (4) a crown ratio function.

Potential Function

Potential diameter growth is the annual diameter increment for a tree in a forest stand free to grow without competition from its neighbors.

A basic premise in the design logic of this forest growth projection system is that the growth of a tree can be represented by a multiplicative combination

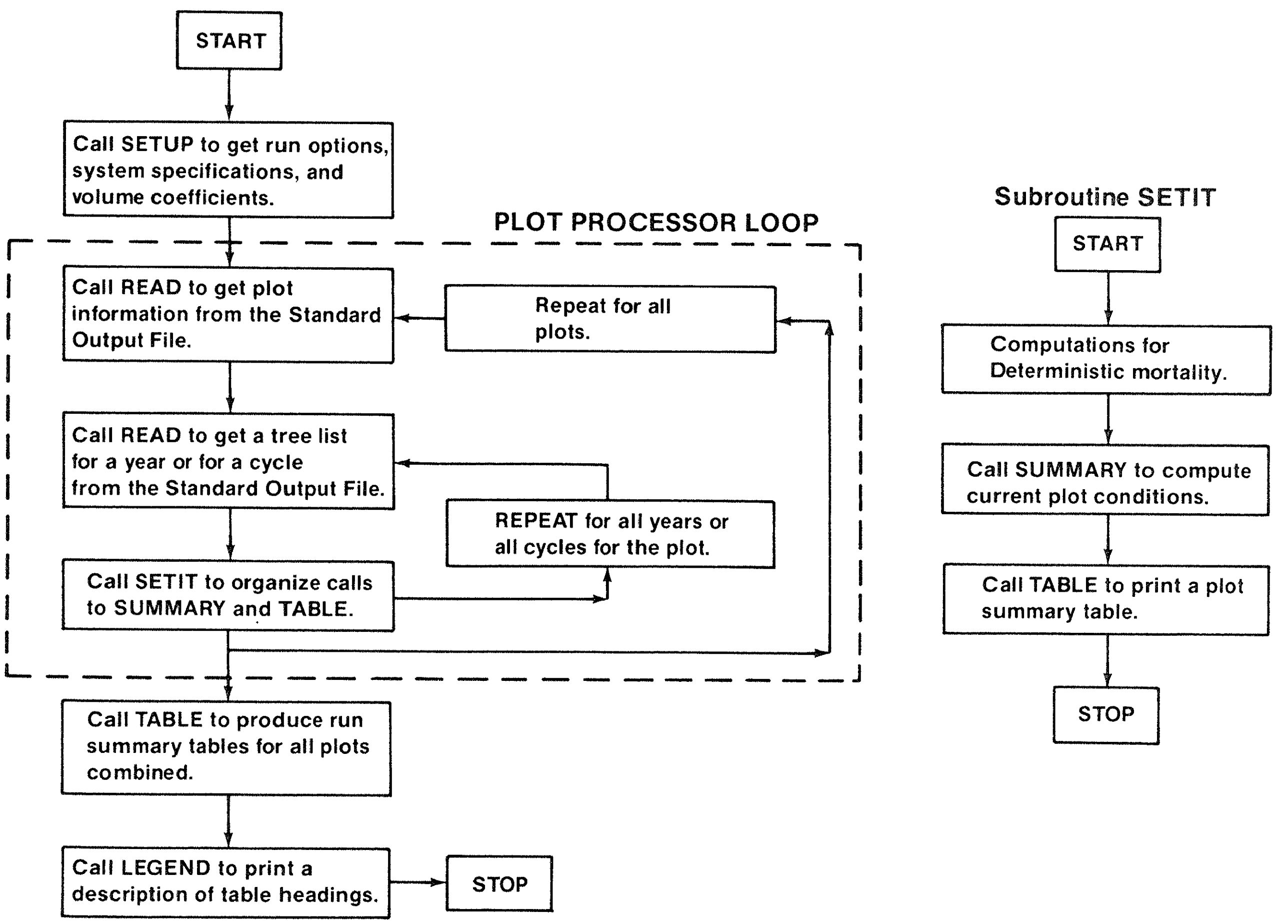

Figure 3.—*Organization of TABL, standard summary routine.*

of a potential growth and a modifier of the potential due to competition. These two parts fit together as shown below:

$$\text{Annual change in tree diameter} = \left[\begin{array}{l}\text{Potential annual}\\ \text{d.b.h. growth}\end{array}\right] \times \left[\begin{array}{l}\text{Fraction of the potential}\\ \text{growth actually occurring}\end{array}\right]$$

Following is the potential diameter growth function used in STEMS (Hahn and Leary 1979):

Potential annual diameter growth rate = $b_1 + b_2 D^{b_3} + b_4 SI\ CR\ D^{b_5}$

where:

- D = initial tree d.b.h.;
- SI = plot site index;
- CR = tree crown ratio code;
- $b_1 - b_5$ = species specific regression coefficients.

Data used to fit this model came from two successive measurements made on 51,149 dominant and codominant trees of 26 species groups throughout Michigan, Minnesota, and Wisconsin (Christensen *et al.* 1979). Variables measured for each tree included diameter, crown ratio code[1] at the last measurement, and plot site index.

Work by Carmean (1979) and Carmean and Vasilevsky (1971) has provided a means for predicting the site index for each species group from the plot site index. In the current version of STEMS, species site index rather than plot site index is used in the potential function.

A graph of potential growth for the black and green ash species group shows that a tree with a diameter of 10 inches, site index of 60, and crown ratio code of 3 would have a potential growth of about 0.15 inch per year (fig. 4). As site index increases, potential growth increases. However, potential growth peaks between 15 and 20 inches d.b.h. regardless of site index.

Modifier Function

The modifier function in the original version of the projection system used a stand component approach (Leary and Holdaway 1979). In STEMS, the function has evolved into an individual tree modifier (Hahn *et al.* 1979). The current form as developed by Holdaway[2] and used in STEMS is:

$$\text{MODIFIER} = 1 - e^{-B_o \left[\frac{BA_{max} - BA}{BA}\right]^{.5}}$$

where:

- BA_{max} = maximum basal area per acre expected for the species;
- BA = current basal area per acre;
- B_o = $f(R) \cdot g(AD)$;
- R = relative d.b.h. of the tree (ratio of the tree's d.b.h. to the average stand diameter);
- AD = average stand diameter;
- f(R) = a function characterizing the individual tree's relative diameter effect on the modifier $f(R) = b_1 [1 - e^{b_2 R}]^{b_3} + b_4$;
- g(AD) = a function characterizing the average stand diameter effect $g(AD) = c_1 (AD + 1)^{c_2}$; and
- $b_1, b_2, b_3, b_4, c_1, c_2$ = regression coefficients.

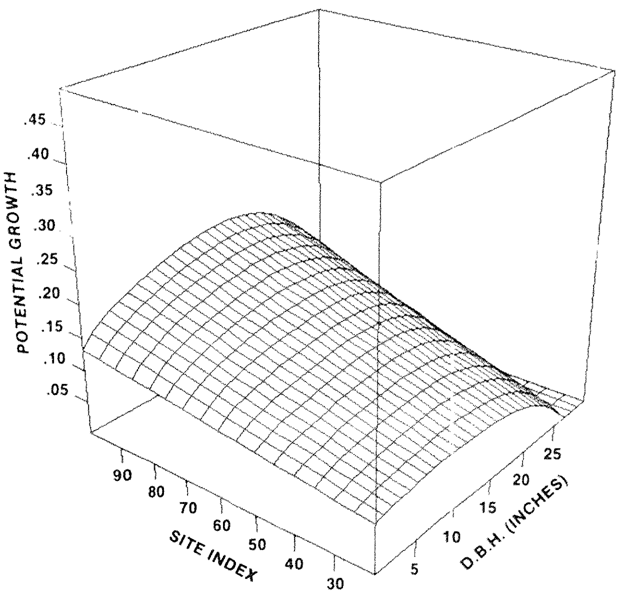

Figure 4.—*Potential annual diameter growth (in inches) for the black and green ash species group with crown ratio code = 3.*

[1] *See the section on crown ratio function for a definition of the crown ratio code.*

[2] *Reported in unpublished manuscript by Margaret Holdaway, Mathematical Statistician, North Central Forest Experiment Station, St. Paul, Minnesota.*

Trees on less dense stands keep a higher percentage of their potential growth than those on dense stands (fig. 5). For example: a 10-inch tree on a stand with average diameter of 8 inches (relative diameter = 10/8 = 1.25) and with plot basal area of 100 ft^2/acre realizes only about 70 percent of its estimated potential growth.

The results of the potential and modifier functions can be combined to produce a realized growth function (fig. 6). Consider a green ash tree with a 10-inch diameter and crown ratio code of 3, growing in a stand with a site index of 60, average diameter of 8 inches, and plot basal area of 100 ft^2/acre. The potential function estimates an annual growth of 0.15 inch, but the modifier estimates that only 70 percent of that growth will occur so the realized growth for this tree is 0.10 inch.

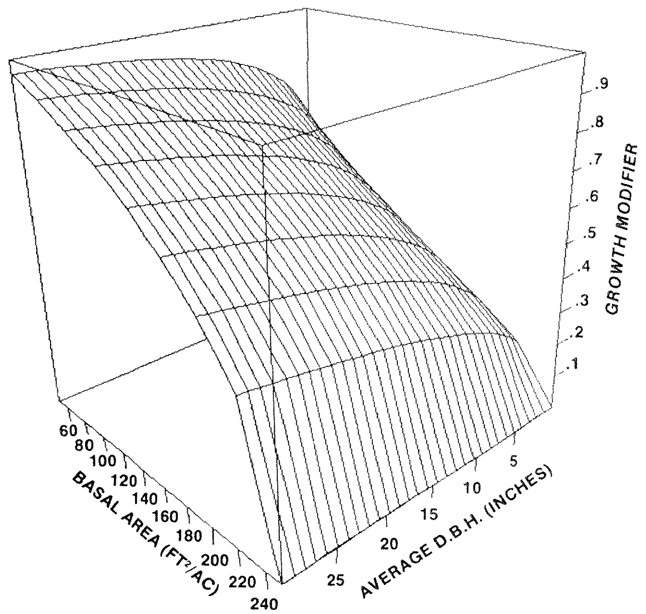

Figure 5.—*Growth modifier function for the black and green ash species group with relative diameter = 1.25.*

Mortality Function

The process of natural mortality in a forest stand is simulated by applying the mortality function developed by Buchman (1979). This function predicts the probability of death of an individual tree during a 1-year period as a function of the tree's current d.b.h. and its annual growth rate.

The form of the equation is:

$$P = \left[1 + e^{(b_1 + b_2\, DGR^{b_3} + b_4 D)}\right]^{-1} + b_5$$

where:

P = estimated probability of a tree dying;
b_1 = adjustment for diameter effect when DGR is zero;
b_2, b_3 = adjust probability of dying based on DGR;
DGR = annual diameter growth rate in inches;
b_4 = adjustment based on tree size;
D = diameter at breast height in inches; and
b_5 = background annual death rate.

The regression coefficients—b_1, b_2, b_3, b_4, and b_5—were determined separately for each species group.

A graph of the mortality function for black and green ash shows it is unlikely that a tree will die if its growth rate is greater than 0.08 inch per year (fig. 7). A tree with a growth rate of 0.10 inch per year has less than a 1 percent chance of dying.

STEMS provides two ways to assign mortality to individual trees. The options are known as probabilistic and deterministic mortality and are selected by the appropriate TGPS run option. The difference between the two options is the way the mortality factor is applied. For probabilistic mortality, a random number is drawn from a uniform distribution between 0 and 1. If the probability of death is greater than this random number, the tree and all the trees that it represents are marked as dead. For deterministic mortality, the number of trees per acre that

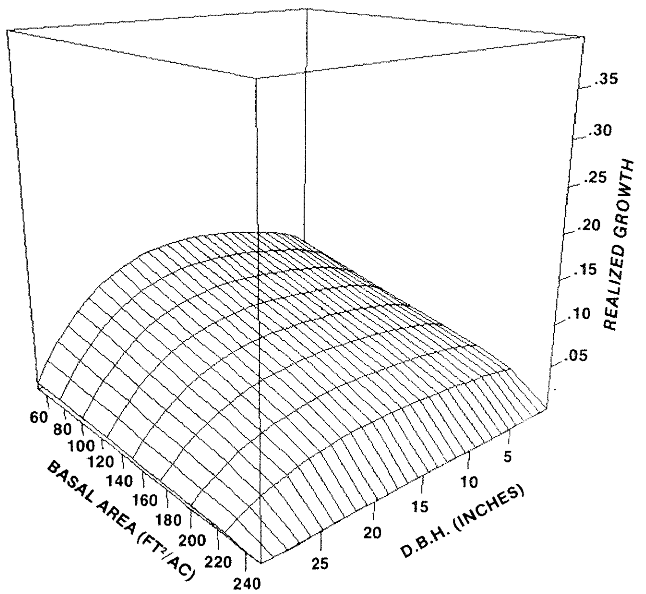

Figure 6.—*Realized annual growth for the black and green ash species group for trees with crown ratio code of 3 in a stand with site index of 60 and average diameter of 8 inches.*

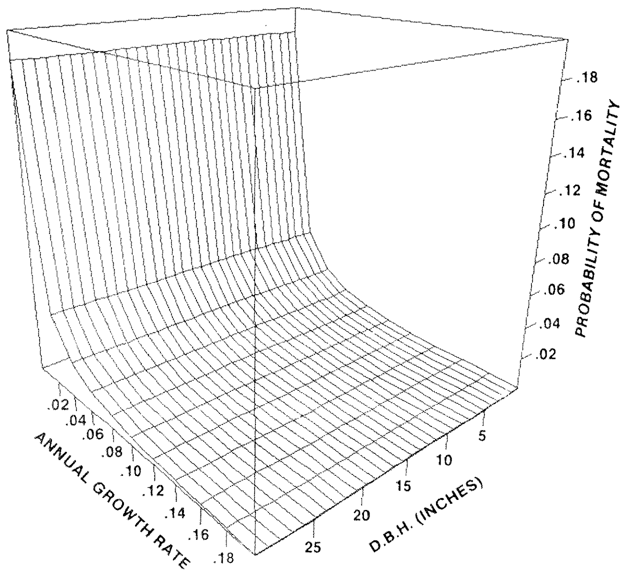

Figure 7.—*Annual probability of mortality for the black and green ash species group.*

this tree represents is reduced by the proportion predicted by the mortality function. When a tree's expansion factor is reduced to 1, mortality type reverts to probabilistic so that a tree on the tree list will not represent less than one tree per acre.

Each type of mortality has advantages and disadvantages and it is up to the user to decide the option appropriate to his situation. For large numbers of plots and short projections (less than 30 years), the two options produce the same results. Probabilistic mortality is more computationally efficient than deterministic but for long projections it can have undesirable results. A plot may be reduced through mortality or cutting to two or three entries on the tree list and each tree on the list represents about one-half or one-third of the basal area per acre. If one of these trees dies, the plot loses a large portion of its basal area at once. This may not be a reasonable representation of natural mortality. The deterministic option does not have this problem because it retains the tree list entries for a much longer period. However, more computations are required and annual output of tree lists is necessary when a summary of growth components is desired. For large numbers of plots the size of the output file can become critical. The probabilistic option produces a shorter output file for the same components of growth summaries.

Crown Ratio Function

To allow the model to respond to changes in stand density and to allow the potential function to be used when crown ratio was not measured, a crown ratio code function has been developed to estimate crown ratio codes according to stand basal area and individual tree d.b.h. The code 1, 2, ..., 9, 0 represents crown ratios of from 1 to 10 percent, 11 to 20 percent, ..., 81 to 90 percent, and 91 to 100 percent, respectively. Application of this function makes crown ratio a dynamic variable within the simulation program and thus increases the precision of projections. The function can also be used to compute an initial crown ratio code for those trees for which crown ratio was not measured.

The crown ratio code function used in the original version of the growth projection system predicted mean stand crown ratio code (Holdaway *et al.* 1979). Subsequent development[3] has resulted in the following individual tree crown ratio code function now used in STEMS (fig. 8):

$$CR = \frac{b_1}{1 + b_2 BA} + b_3 \left[1 - e^{-b_4 D}\right] + CF$$

where:

CR = individual tree crown ratio code;
BA = 10-year running average stand basal area per acre;
D = current tree diameter (d.b.h.);
CF = correction factor computed as: initial predicted CR–initial observed CR; and
b_1, b_2, b_3, b_4 = species specific regression coefficients.

The model was calibrated using current stand basal area for the BA term but STEMS uses a 10-year running average stand basal area for this term. This usage produces a desirable lag in the function's response to drastic changes such as thinnings.

[3]*Documentation for the crown ratio code function is currently being prepared by Margaret Holdaway, Mathematical Statistician, North Central Forest Experiment Station, St. Paul, Minnesota.*

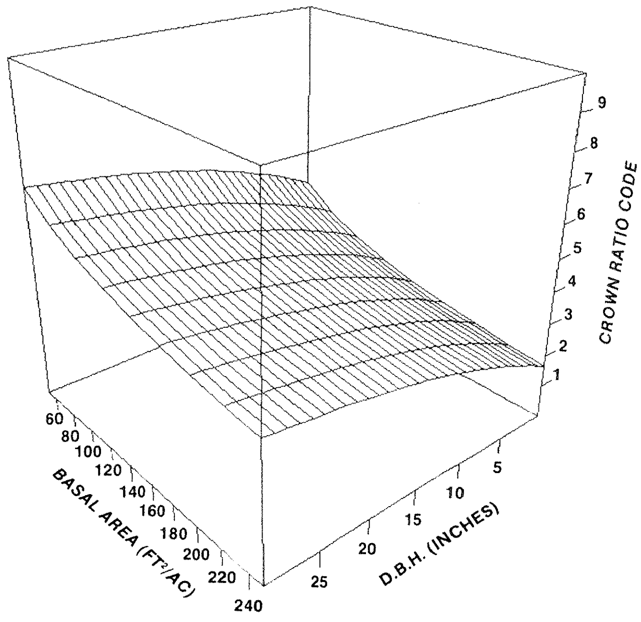

Figure 8.—*Crown ratio code for the jack pine species group.*

MANAGEMENT SUBSYSTEM

The projection system contains a set of generalized management guides and marking rules (Brand 1979, 1981b). Including management guides allows simulated tree cutting and thereby a means to project managed stands. Three operations are necessary to simulate timber management: assigning a management guide, determining the appropriate treatment according to that guide, and removing trees to carry out the selected treatment.

The first step in assigning a management guide is to determine the plot cover type by examining the basal areas of trees of each species group. To do this, various combinations of species group basal areas are compared to determine the group with the largest basal area. The combination with the largest basal area is then split into smaller groups that are then compared. This process is continued until a single species or a small group of species remains to represent a cover type. For example, red pine cover type is represented by red pine species, but northern hardwood cover type is represented by any combination of sugar maple, basswood, hemlock, and yellow birch species. The user specifies the management guide to be used for each cover type via input from the system parameters and specifications file.

When the management guide has been assigned, the plot characteristics are used to select the appropriate silvicultural treatment—clearcut, thin, do nothing, etc. Management guides recently developed by North Central Forest Experiment Station scientists were used to select treatments for most of the cover types (Benzie 1977a, 1977b; Johnston 1977a, 1977b; Perala 1977; Sander 1977; Tubbs 1977). Additional sources were used for other types and additional clarification (USDA Forest Service 1958, 1967, 1979).[4] When plot characteristics are compared with the management guide, a recommended treatment is produced. Rotation ages, residual basal areas, and the other characteristics used in the management guides can be easily modified to test the effect of alternative management strategies.

A marking rule was developed for each recommend treatment that requires trees to be cut. This marking rule produces a hierarchy of characteristics used to rank the trees on the plot in order of increasing "value," which is determined by species, diameter, and tree quality. The least "valuable" trees are cut first. When the desired residual conditions exist, no more trees are cut. The trees designated as cut still remain on the tree list but with a cut tree status code. A marking rule can be easily changed to examine the effect of not removing cull trees, favoring alternative species, or favoring different size classes. Brand (1979, 1981b) describes the management subsystem in more detail.

REGENERATION SUBSYSTEM

Regeneration in a forest growth simulator is the process of adding new trees to the system. This process can be divided into three categories for modeling purposes. The first category includes the small number of new trees that will become established each year in almost every stand. These new trees will differ as to species and most of them will die during the first few years of their lives. Depending on the characteristics of the stand they enter, however, some may survive and become "permanent" components of the stand. The second category, "partial" regeneration, represents the new trees that normally enter a stand to fill spaces left by thinnings, heavy

[4]*Personal communication with John Benzie, Richard Godman, William Johnston, and Donald Perala, all scientists with the North Central Forest Experiment Station.*

mortality, or other occurrences that leave moderately sized holes in the existing stand. The third category, "initial" regeneration, represents the totally new stand that must be generated when the existing stand has been completely removed through clearcut or equivalent management action. This condition is common for forest types under even-aged management such as red pine and jack pine but is uncommon for forest types under uneven-aged management such as northern hardwoods.

We do not now have the data on which to base a function to model either the first or second category of regeneration. However, we have developed a model for "initial" regeneration. Simulation of "initial" regeneration consists of two steps. The first step is to determine the characteristics of the new stand—species groups present, number of trees, average diameter, etc. The second step is to generate a diameter distribution for the new trees. Only these two steps are discussed here.

Characteristics of the new stand are based on both previous stand's characteristics and the type of management used to remove the previous stand. Decision trees have been developed[5] for most of the major cover types that lead from the previous stand characteristics to those of the new stand. As an example, when a paper birch stand on a dry site is clearcut, the recommended regeneration technique is to prepare the site and plant 900 jack pine trees per acre (fig. 9). The resulting stand will have an average diameter of 1.5 inches when it enters the projection system and release will probably be required. If the previous stand had not been dry or if a shelterwood removal had been done rather than a clearcut, the new stand would have different characteristics.

When the new plot characteristics have been determined, a diameter distribution must be generated for the new trees. STEMS arbitrarily assumes a normal distribution of diameters about the average stand diameter. The normal distribution is probably not the best one for modeling a regenerated stand and we are currently trying to develop a more realistic method for generating the new diameters. However, we will use the normal distribution until this work is complete.

Currently STEMS assumes that any regenerated stand will enter the projection system 15 years after the previous stand is removed. In future versions of STEMS this number will be set in the decision trees.

[5]*Nancy Walters and Gary Brand of North Central Forest Experiment Station.*

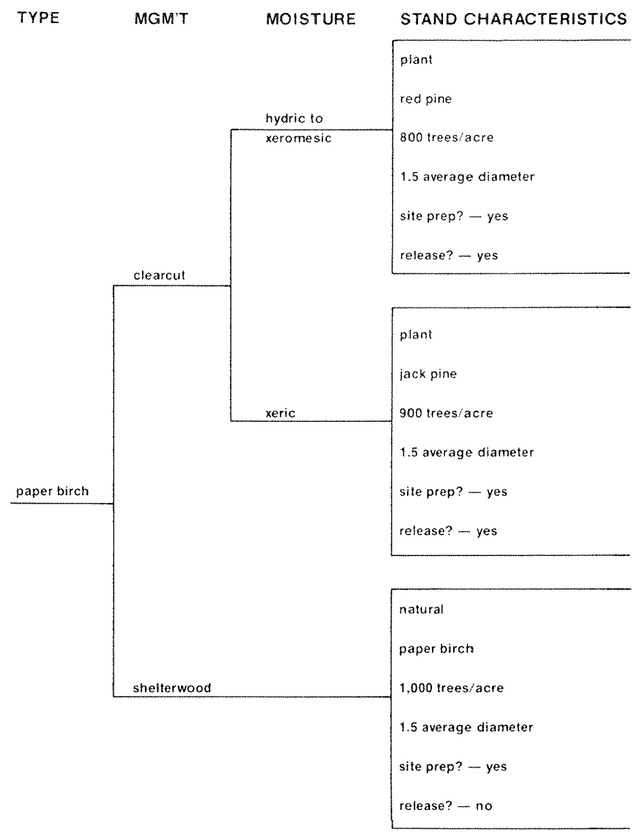

Figure 9.—*Decision tree for regenerating a stand that was previously paper birch.*

The user can easily change any of the values associated with the regeneration subsystem by modifying the system parameters and specifications data file (Belcher 1981).

TESTING STEMS

As each component of the system was developed, we tested it against the data used in development and against an independent data set using the usual indices of goodness of fit (R^2, distribution of residuals, and standard errors of estimates). Then, to determine how the system worked as a whole we subjected it to a second set of tests. First, the system was tested on the data used to develop the components to see if it could reasonably simulate the conditions used to develop it. Results from these tests do not appear here. Next, the system was tested on data not used in model calibration. Tables 1-3 were produced using this independent data set. The statistic used in this and further system tests was the ratio of predicted to observed means. The tests presented here follow the procedure outlined by Leary *et al.* (1979).

Table 1.—*Ratio of predicted mean to observed mean*[1] *for average diameter, number of trees, and basal area by forest type for the Cloquet Experimental Forest*

Forest type	Plots	Years after initial measurement								
		5	10	17	5	10	17	5	10	17
	Number	*Average plot diameter*			*Number of trees*			*Basal area*		
Jack pine	79	1.00	1.00	1.00	1.00	1.01	1.04	1.00	1.01	1.04
Red pine	49	1.00	1.00	.99	1.00	.99	1.01	1.00	1.00	1.00
White pine	6	.99	.97	.96	1.05	1.12	1.16	1.03	1.06	1.06
White spruce	4	.99	1.03	.98	1.01	1.13	1.09	1.04	1.24	1.12
Balsam fir	23	1.02	1.03	1.06	1.04	1.09	1.19	1.09	1.18	1.31
Black spruce	29	1.02	1.03	1.06	1.05	1.08	1.16	1.07	1.13	1.29
Tamarack	19	1.01	1.02	1.03	.97	.92	.87	1.00	1.01	1.06
N. white-cedar	14	1.01	1.03	1.05	1.03	1.04	1.10	1.06	1.12	1.23
Lowland hdwds	3	1.00	1.02	1.01	1.07	1.06	1.28	1.08	1.11	1.32
Aspen	30	1.01	1.02	1.04	1.01	1.03	1.07	1.05	1.10	1.19
Paper birch	36	1.00	1.02	1.03	1.02	1.02	1.03	1.04	1.05	1.09
ALL	292	1.00	1.01	1.02	1.02	1.02	1.06	1.03	1.05	1.09

[1]Calculated as: $\frac{\text{predicted mean stand attribute for the type}}{\text{observed mean stand attribute for the type.}}$

STEMS was tested[6] on data from five areas within the Lake States (fig. 10):

(1) Cloquet Experimental Forest of the College of Forestry[7], University of Minnesota;
(2) Chequamegon National Forest, Wisconsin;
(3) Nicolet National Forest, Wisconsin;
(4) Hiawatha National Forest, Michigan; and
(5) Manistee National Forest, Michigan.

[6]*Most of the work done on testing the STEMS program was done by Gary Brand and Margaret Holdaway with assistance from Stephen Shifley and Jerold Hahn, all of the North Central Forest Experiment Station, St. Paul, Minnesota.*

[7]*Dietmar Rose and the staff of the Clóquet Forestry Center made the past measurement data available and assisted in the 1976 measurements.*

Table 2.—*Summary of the ratio of predicted mean basal area to observed mean basal area by forest type for the measurement closest to 10 years for each of the five forest areas (The number of plots appear in parenthesis)*

Forest type	Cloquet (10 yrs)	Chequamegon (11 yrs)	Nicolet (11 yrs)	Hiawatha (9 yrs)	Manistee (11 yrs)	ALL
Jack pine	1.01 (79)	1.08 (7)	1.08 (6)	1.08 (20)	1.05 (15)	1.03(127)
Red pine	1.00 (49)	1.06 (6)	.93 (4)	.92 (11)	1.01 (15)	.99 (85)
White pine	1.06 (6)	1.00 (2)	.93 (2)	1.00 (3)		1.01 (13)
White spruce	1.24 (4)	.78 (1)	.99 (4)	.93 (1)		1.07 (10)
Balsam fir	1.18 (23)	1.06 (14)	1.08 (8)	1.39 (6)		1.15 (51)
Black spruce	1.13 (29)	.93 (2)	1.62 (3)	1.12 (6)		1.16 (40)
Tamarack	1.01 (19)	1.02 (2)	.77 (2)			.98 (23)
N. white-cedar	1.12 (14)	1.07 (8)	1.05 (9)	1.06 (14)	1.37 (2)	1.08 (47)
Hemlock			.93 (4)	.96 (3)		.95 (7)
Lowland hdwds	1.11 (3)	1.31 (5)	1.09 (2)	.92 (1)	1.47 (19)	1.34 (30)
Northern hdwds		1.05 (40)	1.01 (49)	.99 (28)	1.21 (18)	1.04(135)
White oak					.98 (15)	.98 (15)
Northern red oak		1.10 (4)	1.30 (1)	1.03 (2)	1.15 (8)	1.13 (15)
Oak-pine				.78 (1)	1.00 (9)	.47 (10)
Oak-hickory		.40 (1)			.82 (34)	.82 (35)
Aspen	1.10 (30)	1.07 (23)	.98 (42)	1.02 (14)	1.24 (12)	1.05(121)
Paper birch	1.05 (36)	.99 (8)	.99 (9)	1.22 (4)	1.10 (1)	1.05 (58)
ALL	1.05(292)	1.06(123)	1.01(145)	1.03(114)	1.09(148)	1.05(822)

Table 3.—*Summary of the mean of the plot ratios of predicted average diameter to observed average diameter by forest type for the Cloquet Experimental Forest*

Forest type	Plots	Years after initial measurement		
		5	10	17
	Number			
Jack pine	79	1.00	1.00	.99
Red pine	49	.99	1.00	.99
White pine	6	.99	.97	.97
White spruce	4	.99	1.03	.98
Balsam fir	23	1.02	1.04	1.06
Black spruce	29	1.02	1.03	1.06
Tamarack	19	1.01	1.03	1.05
N. white-cedar	14	1.01	1.03	1.05
Lowland hdwds	3	1.00	1.02	1.01
Aspen	30	1.02	1.03	1.05
Paper birch	36	1.01	1.02	1.04
ALL	292	1.01	1.01	1.02

Ratios were computed for plot average diameter, number of trees, and basal area to give a representative picture of system performance. In general, the whole system accurately predicted diameters but overpredicted basal areas per acre over periods ranging from 5 to 17 years.

As the number of plots increases and the number of years of projection decreases, the ratio of predicted to observed mean moves closer to one (table 1). For example: on the Cloquet Forest there were 49 plots of the red pine forest type and 6 plots of the white pine forest type. After 17 years of projection the ratio of predicted to observed mean average diameter was 0.99 for red pine—a 1 percent underestimate—but was 0.96 for white pine—a 4 percent underestimate.

A comparison of the ratio of mean stand basal areas by location indicates the variability between locations (table 2). For example, the predicted mean stand basal areas for the 14 aspen plots on the Hiawatha Forest show an overprediction of only 2 percent. In contrast, the 12 aspen plots on the Manistee Forest show a 24 percent overprediction.

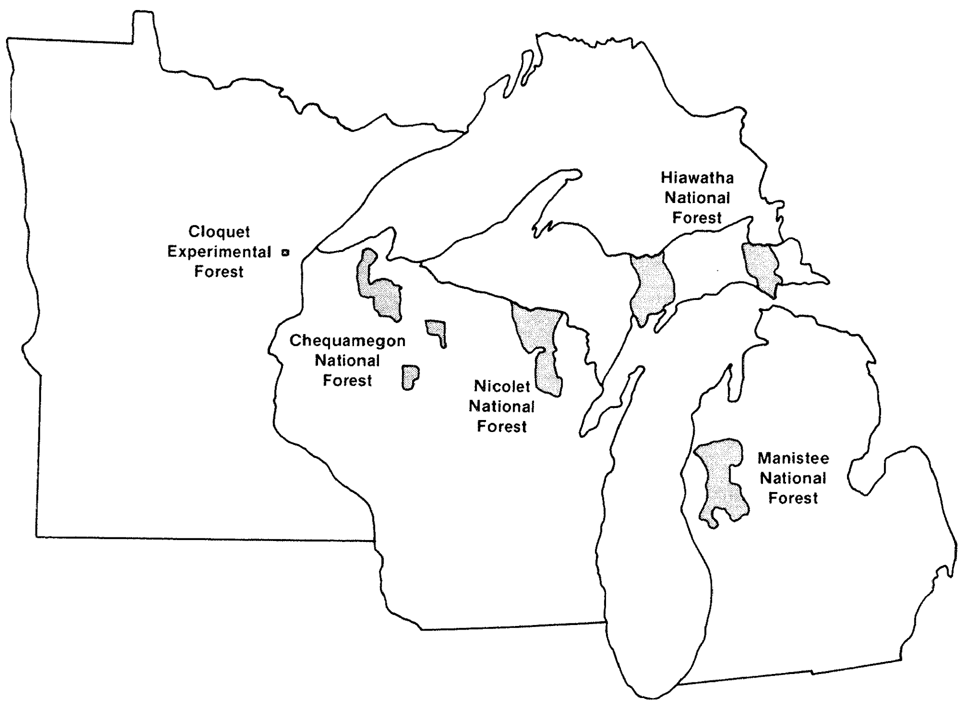

Figure 10.—*Location of areas where data were collected to validate the model.*

Tables 1 and 2 show ratios of mean stand characteristics, i.e.:

$$\text{ratio} = \frac{\frac{1}{n}\sum_{i=1}^{n} \text{predicted value}_i}{\frac{1}{n}\sum_{i=1}^{n} \text{observed value}_i}$$

where n is the number of plots on which the mean is based. Table 3, however, presents the mean of ratios of a stand characteristic, i.e.:

$$\text{mean} = \frac{1}{n}\sum_{i=1}^{n} \frac{\text{predicted value}_i}{\text{observed value}_i}$$

This later statistic allows computation of dispersion measures such as variance of the plot ratios about the mean of plot ratios. The mean of ratios of predicted to observed stand average diameter by forest type can also be graphed over time (fig. 11). Approximately 68 percent of the stand average diameter ratios are expected to fall within +1 and −1 standard deviation from the mean.

Another method of presenting dispersion of a characteristic being tested is to plot its cumulative frequency of errors.[8] A graph of this type for the four National Forests shows that basal area for 16 percent of the plots on these four forests was underpredicted by more than 10 ft^2 and for 23 percent of the plots was overpredicted by more than 10 ft^2 for a period of about 10 years (fig. 12). For the remainder of the plots, 61 percent, predicted basal area was within 10 ft^2 of the observed basal area.

The validation results presented in this discussion represent only a few of the tests that can be and are being done[9] to validate the model.

EXAMPLE USING STEMS

We will now present an example of how STEMS can be used. For this example, two 30-year projections have been made of sample plots representing the Nicolet National Forest. One projection is made with management applied (full silvicultural prescription with timber harvesting) and the other is made with no management (no timber harvesting). No constraints will be placed on when the forest can be managed. That is, should the STEMS management guides call for all plots to be harvested in the same year, that will be done. This will allow us to compare between two management extremes.

The plots providing the data were last measured in 1975. To begin the 30-year projections with more current conditions, the 1975 survey has been updated to 1979, the last year for which actual removals were known. The updating procedure involves beginning with the 1975 survey and estimating growth and mortality with the projection system while selecting trees to cut to approximate the observed volume removed from the forest (Smith and Raile 1979).

The following plot and tree variables were read from a forest survey file to produce an initial tree list:

Tree data	**Plot data**
Species	Property number
D.b.h.	Plot number
Crown ratio	Site index
Tree class (desirable, acceptable, rough, rotten)	Stand age
Number of trees/acre represented by the sample tree	Cover type
	Acreage represented by plot
	Measurement year

All variables are required by the projection system except property number, plot number, cover type, and plot acreage.

All volumes used in this example were computed from individual tree characteristics using equations and coefficients developed for northeast Minnesota (Raile 1981). These equations were chosen instead of the local volume equations available for Wisconsin (the Nicolet National Forest is in Wisconsin) because the Minnesota equations contain a site index term and the Wisconsin equations do not. We believe including the site index term will make the computed volumes more accurate even though the equations were developed for a different geographical region.

Many types of summaries and displays can be developed from the tree lists produced by STEMS. For this example, we will present information on acreage and volume of growing stock, cut and mortality volumes, trends in species composition, and size distribution.

[8] *This approach was suggested by Steven Shifley, North Central Forest Experiment Station.*

[9] *Gary Brand and Margaret Holdaway, North Central Forest Experiment Station, are currently performing a comprehensive validation scheme for the projection system.*

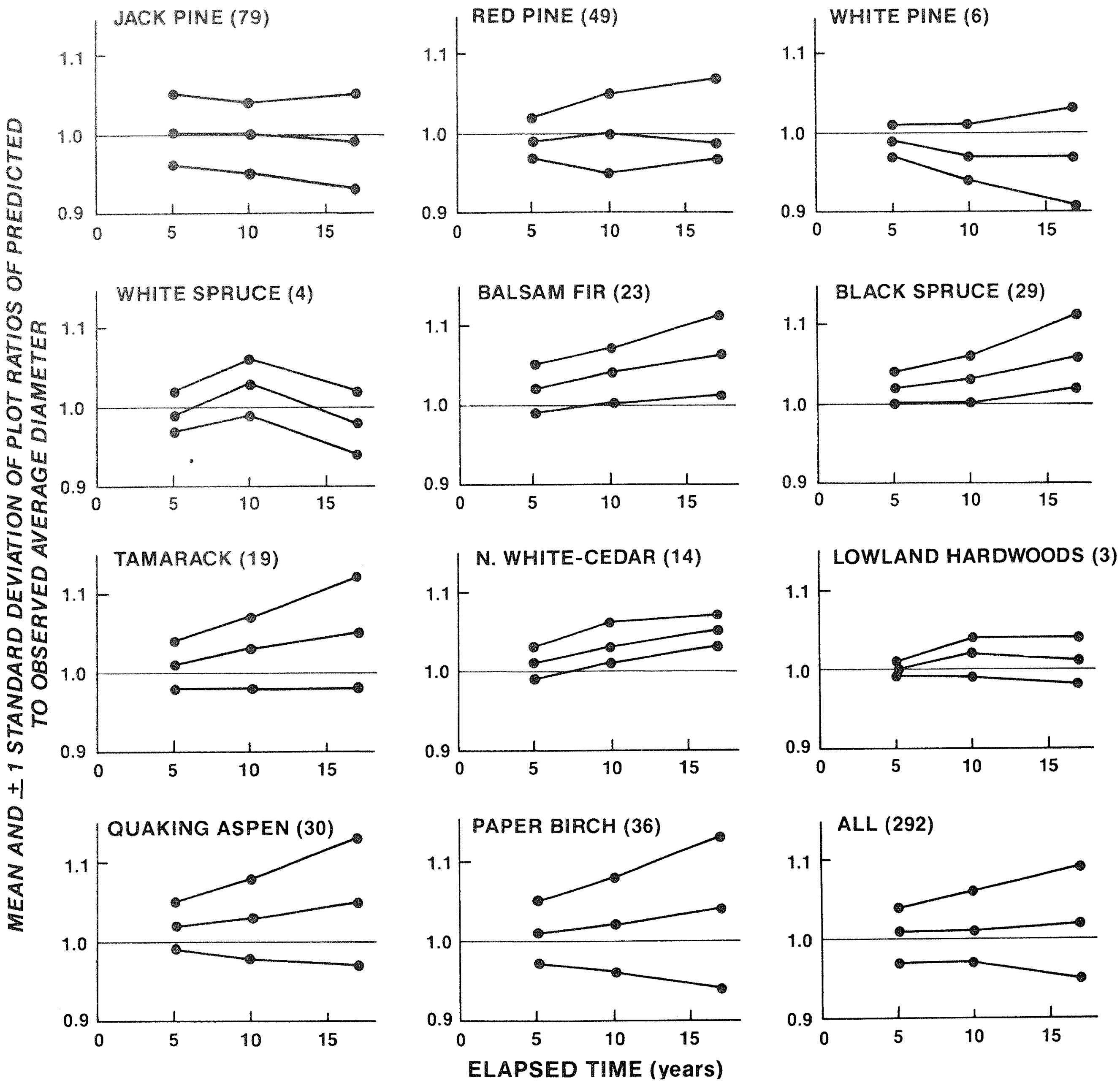

Figure 11.—*Pattern of mean and standard deviation of plot ratios of predicted to observed average diameter by forest types on the Cloquet Experimental Forest, Minnesota. Standard deviations are shown by the outer lines. Number of plots shown in parentheses.*

Acreage and volume of growing stock for 1979 through 2009 are presented for the Nicolet National Forest with management applied and with no management (tables 4 and 5). The distribution of area changes because STEMS reclassifies the cover type of stands that have sufficient change in species composition. Species composition can change by loss of trees due to mortality, cutting, and by regeneration of stands to different species groups.

The overall growth rate for the 30-year period is less when the management guides are applied than when management is not used (fig. 13). This is because the management guides select for value of the forest rather than for volume. Thus, the more valuable species, such as red pine, are preferred over the faster growing species, such as aspen.

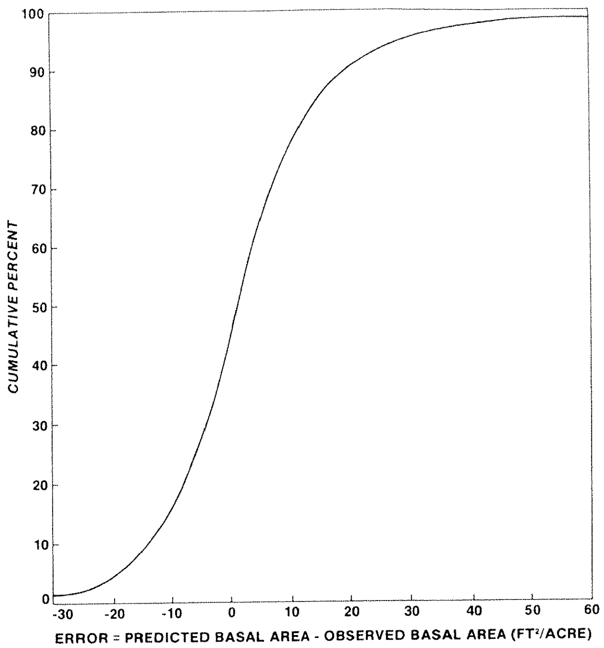

Figure 12.—*Cumulative frequency of errors in predicting basal area for four National Forests. The measurement interval was approximately 10 years.*

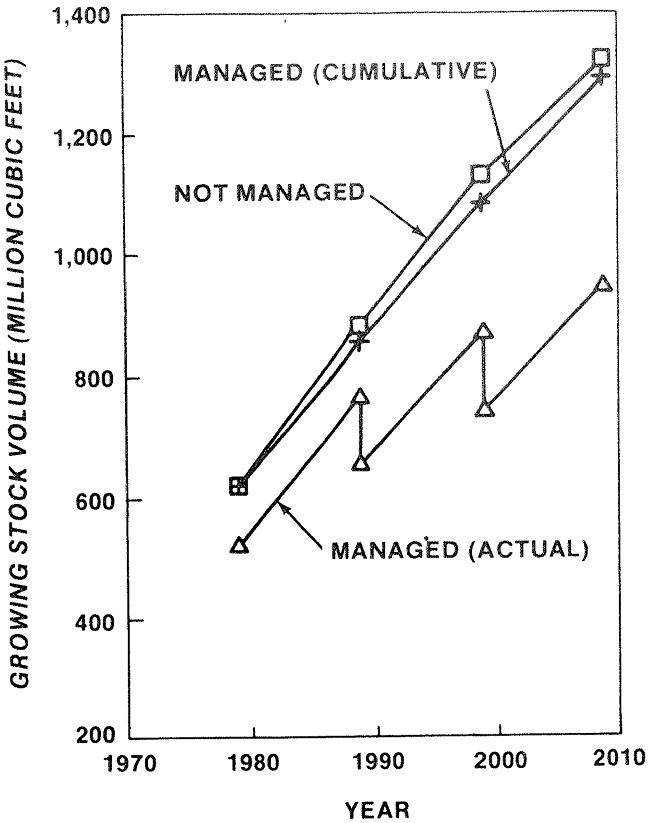

Figure 13.—*Volume of growing stock for Nicolet National Forest, 1979-2009, for all trees with and without management.*

The STEMS management guides recommended that 343.1 million cubic feet of growing stock trees be cut during the 30-year projection period (table 6). Because low value and poorly growing trees would

Table 4.—*Summary of acreage and volume/acre of growing stock on the Nicolet National Forest with management applied (timber harvesting)*

			Projected to					
	Updated to 1979		1989		1999		2009	
Cover type	Acres	Merchantable volume	Acres	Merchantable volume	Acres	Merchantable volume	Acres	Merchantable volume
	Thousand	*Cu ft/ac*	*Thousand*	*Cu ft/ac*	*Thousand*	*Cu ft/ac*	*Thousand*	*Cu ft/ac*
Jack pine	3.4	1,265	3.4	1,682	3.4	2,125	3.4	1,892
Red pine	56.2	1,992	56.2	2,897	95.3	2,328	99.2	2,418
White pine	4.9	1,784	4.9	2,416	4.9	3,012	6.4	2,760
Hemlock	21.7	2,310	21.7	2,070	21.7	2,302	21.7	2,518
Balsam fir	43.7	1,207	38.5	1,154	32.7	1,020	26.7	1,354
Black spruce	8.1	1,213	8.1	1,159	8.1	358	8.1	277
N. white-cedar	31.4	1,417	35.1	1,401	35.1	1,615	37.1	1,852
Tamarack	9.9	1,154	9.9	871	9.9	976	9.9	1,262
White spruce	12.5	1,484	16.5	1,900	18.0	1,773	20.5	1,919
N. red oak	6.9	678	6.9	587	6.9	902	6.9	1,356
B. ash-elm-maple	5.0	437	5.0	531	5.0	846	4.6	936
Maple-beech-birch	213.6	1,626	212.8	1,613	217.1	1,728	217.5	1,732
Aspen	93.4	933	97.2	272	55.0	579	46.9	816
Paper birch	16.3	1,700	13.8	1,567	13.8	2,016	17.0	2,283
Other hardwood	0.4	335	0.4	491	0.4	441	0	0
Noncommercial	3.0	590	0	0	3.1	349	4.6	911
Nonstocked	16.1	0	16.1	0	16.1	0	16.1	0
	546.6	1,432	546.6	1,403	546.6	1,600	546.6	1,736

Table 5.—*Summary of acreage and volume/acre of growing stock on the Nicolet National Forest with no management applied (no timber harvesting)*

Cover type	Updated to 1979		Projected to 1989		Projected to 1999		Projected to 2009	
	Acres	Merchantable volume	Acres	merchantable volume	Acres	Merchantable volume	Acres	Merchantable volume
	Thousand	*Cu ft/ac*	*Thousand*	*Cu ft/ac*	*Thousand*	*Cu ft/ac*	*Thousand*	*Cu ft/ac*
Jack pine	3.4	1,265	3.4	1,619	3.4	1,948	3.4	2,355
Red pine	56.2	1,992	56.2	2,991	56.2	3,936	56.2	4,692
White pine	4.9	1,784	6.4	2,262	6.4	2,863	6.4	3,373
Hemlock	21.7	2,310	21.7	2,335	17.4	2,815	17.4	3,076
Balsam fir	43.7	1,207	32.8	1,324	32.3	1,880	22.7	2,525
Black spruce	8.1	1,213	8.1	1,082	8.1	1,505	8.1	1,927
N. white-cedar	31.4	1,417	31.4	1,569	36.3	1,896	41.5	2,094
Tamarack	9.9	1,154	9.9	918	9.9	964	10.0	1,072
White spruce	12.5	1,484	26.5	1,663	23.9	1,977	25.4	2,268
N. red oak	6.9	678	6.9	944	6.9	1,305	6.9	1,717
B. ash-elm-maple	5.0	437	6.4	576	7.9	839	7.5	1,124
Maple-beech-birch	213.6	1,626	234.9	1,679	241.6	2,119	243.7	2,402
Aspen	93.4	933	59.6	774	54.0	1,164	54.2	1,545
Paper birch	16.3	1,700	16.3	1,813	16.3	2,250	16.3	2,699
Other hardwood	0.4	335	5.4	1,160	5.4	1,327	5.4	1,686
Noncommercial	3.0	590	4.4	625	4.4	848	5.4	753
Nonstocked	16.1	0	16.1	0	16.1	0	16.1	0
	546.6	1,432	546.6	1,615	546.6	2,070	546.6	2,418

be cut, the estimate for mortality volume in the managed projection is approximately half of the estimate for mortality volume in the unmanaged projection. Foresters from the Nicolet National Forest indicated that these mortality estimates were reasonable and well within their expectations.

Comparing the trends in species composition for the 30-year projection with management and without management can indicate the effects of management on the forest (figs. 14 and 15). When management is applied according to the guides within STEMS, hard maple decreases from 18 to 17 percent of the forest's volume. When the forest is allowed to grow with no manmade alterations, hard maple increases to 24 percent of the forest's volume by the year 2009. Quaking aspen drops from 10 to 6 percent with management but only drops to 9 percent without management.

Size distribution of all the trees on the Nicolet National Forest combined (regardless of species) at the beginning and end of the projection period is different with management and without management (fig. 16). With management applied, the 8- and 12-inch diameter classes show almost no change during the projection period. This indicates that the number of trees lost to cutting and mortality in these classes is approximately equal to the growth into these classes.

The managed projection shows more live trees less than 6 inches in diameter in 2009 than the unmanaged projection. This is mostly due to the way regeneration is handled in STEMS. New trees enter the system only after a clearcut or when all the trees on a plot die. These conditions can occur for managed stands but not for unmanaged stands so the small tree component for managed stands is greater.

Table 6.—*Summary of inventory cut and mortality volumes of growing stock trees for the Nicolet National Forest (1979-2009)*
(In million cubic feet)

Period	Managed Initial	Managed Growth	Managed Cut	Managed Dead	Managed Final	Unmanaged Initial	Unmanaged Growth	Unmanaged Dead	Unmanaged Final
1979-1989	616.6	284.9	96.4	38.5	766.6	616.6	320.3	54.1	882.8
1989-1999	766.6	270.2	117.1	44.8	874.8	882.8	326.3	77.4	1,131.6
1999-2009	874.8	248.0	129.6	44.2	949.0	1,131.6	297.9	108.1	1,321.4
ALL	616.6	803.1	343.1	127.5	949.0	616.6	944.5	239.6	1,321.4

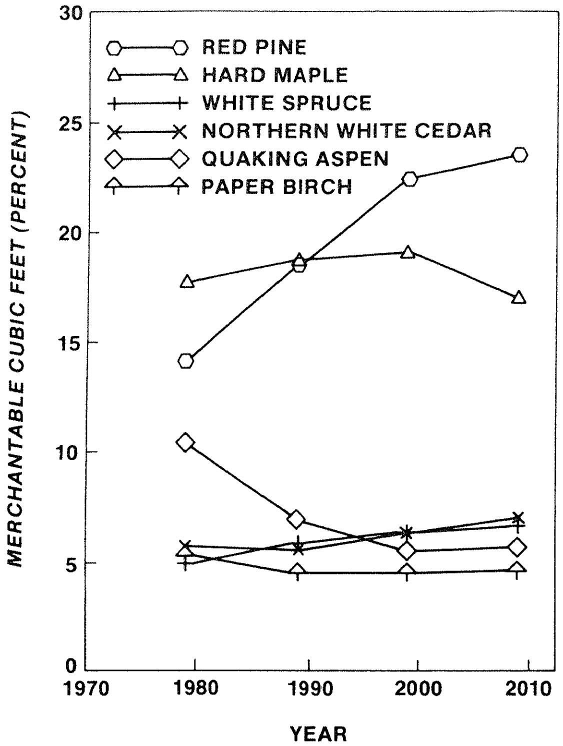

Figure 14.—*Trends in species composition during the 30-year projection period for the Nicolet National Forest when timber management is applied.*

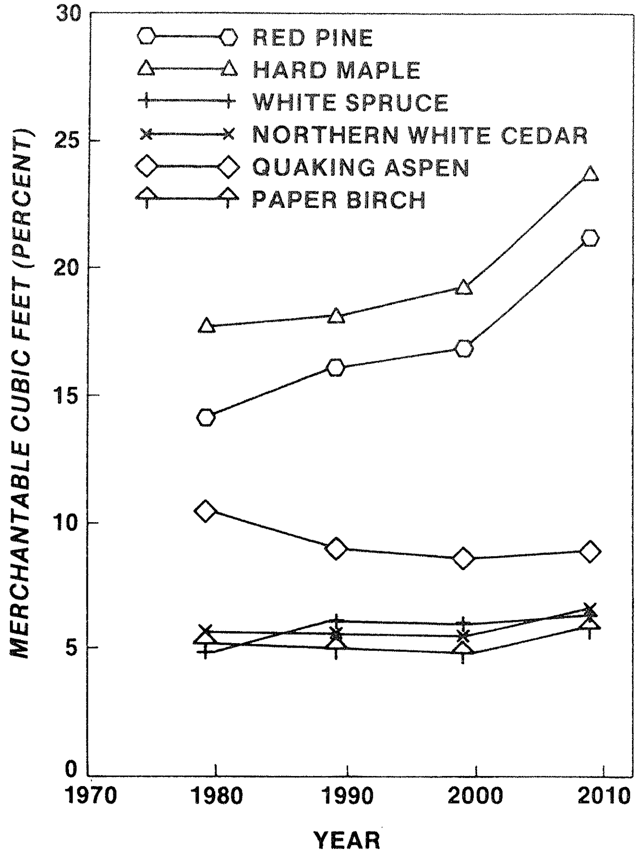

Figure 15.—*Trends in species composition during the 30-year projection period for the Nicolet National Forest when no timber management is applied.*

For diameters greater than 6 inches, the unmanaged projection shows more trees in each size class for 2009. This is because thinning removes trees of these sizes. In unmanaged stands, trees are left to grow with only mortality to remove them. The greater number of large diameter trees for the unmanaged condition again points out that the Lake States management guides used in STEMS managed for value rather than tree size.[10]

CONCLUSION

The Stand and Tree Evaluation and Modeling System (STEMS) is an individual-tree, distance-independent growth simulation model developed for Lake States forest conditions. It uses nonlinear regression equations to project potential tree diameter growth, modify that growth for competition effects, and compute probability of mortality and crown-ratio code

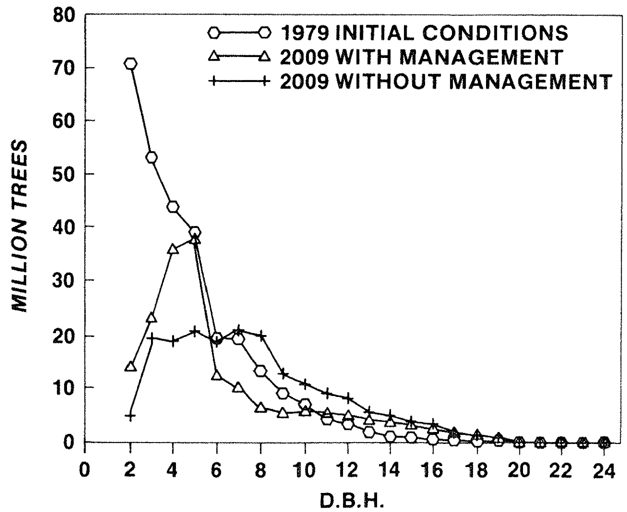

Figure 16.—*Initial and projected size distribution of trees, with and without management.*

[10]*Personel communication with Allen Lundgren, North Central Forest Experiment Station, September, 1980.*

on a tree-by-tree basis. Management and regeneration subsystems are provided to simulate harvest and regeneration of a stand. STEMS can be used to grow single stands or large areas such as National Forests.

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A description of STEMS—the stand and tree evaluation and modeling system. Gen. Tech. Rep. NC-79. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station; 1982. 18 p.

This paper describes STEMS (Stand and Tree Evaluation and Modeling System), the current computerized Lake States tree growth projection system. It presents the program structure, discusses the growth and mortality components, the management subsystem, and the regeneration subsystem. Some preliminary results of model testing are presented and an application is discussed.

KEY WORDS: Simulation, Lake States species, mortality model, regeneration model, management guides, growth model, projection system, FORTRAN, validation.

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