SUCcession SIMulator: A Coniferous Forest Simulator. Model Documentation

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ABSTRACT AND DISCLAIMER

The executive program and operating syntax of the forest growth model SUCSIM IV are outlined in Section A. Lists of parameters, state variables and other quantities, and their values (if constant) are given in Section B. The remainder of the bulletin is devoted to the models used. The quantities given here reflect the state of SUCSIM IV as of summer 1978. The readers are referred to published literature for examples of SUCSIM output. Careful comparison between the text and the program code has been made, but errors (typographical and otherwise) are inevitable in a work of this scope. The authors invite notification of any and all errors and inconsistencies.

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Introduction:

Considerable effort over the past decade has been expended on development of computer simulation models of forest growth. There are two basic classes of models: the "forest mansurational" models and the "ecological models". In the first case, the models are often driven by site class curves with modifications to account for effects of stocking (competition) and other factors. A good example of a "mensurational model" is that reported by Ek and Monserud (1974). Their model is a distance-dependent semi-stochastic simulator of tree growth on small plots. The model takes information on plot size, local height-diameter curves, open-grown crown width and diameter-height relations, and numerous other factors, and simulates reproduction and growth on the plot. Potential height growth is given by the dominant local height growth curve, potential diameter increment given by a function of height and height growth. This growth is modified by the Competition Index which is a function of crown overlap, height, diameter of the subject tree and its competitors, and other factors. The model requires considerable empirical data, but is structured with consideration for data acquisition. The nature of the model allows reasonable short term simulations of growth in the study plots. Extrapolation would be hazardous, and mechanistic analysis of forest dynamics is difficult with a model of this type. Because environment is not explicitly modeled, feedbacks from the "forest" to the environment are impossible, as is simulation of impact of human alteration of the environment.

Similarly, Arney (1972), (1974) modeled crown overlap as competitive stress indices which modify crown shape and bole growth and form. Mitchell (1975) goes so far as to model branch growth of Douglas fir stands; a heavily data dependent model that gives quite realistic simulations of tree growth on small plots. Other modelers make no attempt to grow "trees" at all; their models produce yield tables from equations giving basal area or volume growth as functions of time and stocking. In general, these models provide fair-to-good simulations of managed monoculture stands; their predictive success depends upon the real forest's adherence to the time-dependent site class curves. They are usually heavily dependent on empirical data and are thus poor predictors of response under conditions where original data are lacking. A comprehensive collection of forest simulation models is given in Fries (1974).

The "ecological" approach began with JABOWA, the northeastern forest simulator (Botkin, Janek and Wallis 1972). This model is essentially a Markovian structure that randomly plants trees on a 10 by 10 meter "plot", grows them, and kills them. A principal difference between JABOWA and the mensurational models is that the authors tried to relate growth to environment, not time- or size-dependent site class functions. The model's predictive powers are modest (Thomas Siccama, Yale University, personal communication) but the approach spawned imitators at Oak Ridge National Laboratory (H.H. Shugart, personal communication) and elsewhere. In JABOWA, trees are "grown" as implicit functions of leaf area, moisture and temperature status (defined in terms of soil depth and altitude), and light (expressed as percent full sun). Crude as these relations are, they represent an attempt to define and understand the physical and probabilistic factors that govern forest growth.

Unfortunately, JABOWA, like most of the models discussed above, is expensive and slow. In order to simulate a forest's dynamics, JABOWA must be run many times, and the output averaged. Consequently, it cannot be easily used for example as input to optimization procedures. The "plot" size cannot be expanded because of computer limitations.

We set out to construct a model that is fast, and can simulate forest growth on large areas while being mechanistic enough to provide a useful vehicle for testing ecological ideas. We followed the JABOWA approach to some extent; our tree growth model is similar to theirs, and the basic philosophy of modifying the growth function by environmental variables is similar. Major differences are: (1) we do not grow individual trees but cohorts of trees; (2) our birth-death routines are not Markovian; (3) environment is defined more directly in terms of light, temperature and moisture. The cohort structure of the model allows enormous savings in computer memory and run time and allows simulation of large stands instead of small plots; we consider this to be a major advance in forest simulation.

The models were developed without extensive support for data gathering and validation. They are supported by literature in some cases; others are purely hypothetical, based upon observations and/or suppositions. As our intention was to develop an approach toward large scale simulation of natural and managed forests of varied species composition, as affected by environment and vice versa, we soon found that supportive data and knowledge was largely unavailable. Reed began field work designed to provide data for some of the relations and recent data produced by the Coniferous Forest Biome studies will serve to improve these models.

We discovered early that a complex model could not be understood or properly excersized using a haphazard program. Consequently, development of an efficient executive program was necessary; this development took 1 1/2 years, and 4 versions of SUCSIM. We report here on version IV. The executive algorithem is exceedingly fast and efficient; we have made 500-year simulations in less than 40 seconds of CPU time using less than 40000_8 60-bit words of central memory on the CDC 6400 at the University of Washington. Further, unlike most such programs, the value of any function or parameter at any time can be displayed at the users terminal. The processor was a very simple but powerful syntax. The SUCSIN IV processor was written and developed by Stan Clark.

The growth model and underlying theory of SUCSIM are discussed in Reed (1978) and Reed and Clark (1978). Reed and Clark present some sample simulation runs. We present here only a documentation of the model as of June 1978, primarily for reference use.

We begin with a brief discussion of the SUCSIM IV structure, followed by the run syntax. Finally we present documentation of the model.

SECTION A

Description of the Executive Program and Operating Syntax

A.1 DESCRIPTION OF THE EXECUTIVE PROGRAM

SUCSIM IV consists of two independent subsystems: (1) the forest model itself, coded in standard FORTRAN, and (2) a collection of driver routines. These routines allow the operator to interact with any of the model routines. The operator may, among other things, display or change any variable value, direct that specified variables be printed on an output file at regular intervals, monitor a selection of variables at the terminal as the model runs, read commands from an external file, turn certain modules off or on. This flexible programmings gives the operator considerable freedom and control from the terminal, without the strictures of fixed-format I/O. Further, the algorithem "senses" its environment, knowing whether it is running in batch or interactive mode, and allocates I/O files accordingly. All input commands are printed on the output file so a permanent record of the run is available.

The model driver subsystem allows a hierarchical program structure that has several advantages: the system is defined as a set of objects which are composed of a set of attributes and processes. This programming structure is a feature of SIMULA (Birtwistle et al., 1973) and other higher-level languages, none of which are currently in a stable form on the University of Washington's central computer system. We incorporated the ideas in our FORTRAN-based programming which was very successful. In our case, objects are organizing concepts: COHORT, SPECIES, CELL and RUN. Object COHORT contains attributes that are characteristics shared by all sets of trees in the forest: an identification number, basal diameter, height, leaf biomass, age, species, and so on. Object SPECIES is composed of attributes that are specific to tree species: numerous parameters, and some functions that are species-specific, eg. the effect of temperature on growth. The attributes of Object RUN include time, print interval and other I/O factors. The quantities common to cells (plots) are contained in Object CELL: total population, cell area (usually one hectare), environmental factors, etc. Objects and their attributes are related by PROCESSES, e.g. cohort growth, species establishment, light attenuation.

This program structure has several advantages: (1) it allows coherent formulation of the model and code minimizing haphazard model structures that ultimately are incomprehensible or impossible to program, (2) it facilitates variable-reference from the terminal, and (3) allows programming for dynamic variation in the number of objects residing in the system at any time. This structure has led to a very clear, concise model and program that allows maximum flexibility, access to component models and variables, and a highly efficient memory management system.

As an example of the power and flexibility of the OBJECT/ATTRIBUTE approach, consider the variety of listing possibilities provided by SUCSIM. With a single command, the operator may display at the terminal:

(1) A single attribute of a particular object
(2) A single attribute across all objects having that attribute
(3) All attributes of a particular object
(4) All attributes of all objects of a particular type
(5) All attributes of all objects of all types

This program greatly facilitates debugging and comprehension of the program, an important feature lacking in many model structures.

The processes of the model were designed as separate modules for easy maintenance and reference by the operator. Execution of a single one-year time step consists of calls to the light, growth, litterfall, mortality, browsing, establishment and state variable update modules. Several of the processes (litterfall, mortality, browsing, and establishment) can be turned on or off from the terminal. This flexibility allows simulation of "controlled experiments": comparison of runs with some processes on or off. Reed and Clark (1978) provide an example. They addressed the question of optimal stocking level of a single species under different environments. In this case, they "planted" specified numbers of seedlings in the cell and allowed them to grow for 100 "years". The establishment, browse and mortality processes were turned off. By comparing the growth and yield outputs, they could evaluate the effects of crowding alone on productivity. Stepwise addition of establishment,mortality and other routines would allow analysis of the relative impact of those factors.

At present, execution order is fixed. An algorithem has been developed to allow independent scheduling of events, but has not been implemented. Terminal-controlled plotting and other conveniences are planne The SUCSIM driver routines could be used for other similarly-structured models, but at present, the algorithem is written to optimize execution on the CDC 6000-7000 series computers. Documentation within the program listing is adequate to allow a good programmer to rewrite the system driver and executive routines for other computer systems.

A.2 OPERATING SYNTAX OF SUCSIM IV

This operating syntax consists of a set of commands that can be optionally spelled out or abbreviated. Some commands are followed by a string of parameters that constrain or delimit the operation of the command. All parameters must be separated by a comma (,) or equal sign (=) as appropriate; blanks are always ignored. All command names may be abbreviated to the minimum character string which serves to uniquely identify the command. REREAD, for example, may be given as RER, RERE, REREA, or REREAD, but R or RE are not accepted, since they might be interpreted as either READ or REREAD. In the following explanations, the minimum abbreviation is underlined. Optional parameters are enclosed in square brackets[XXXX]. Any command may be terminated by a colon (:) then followed by comments which are printed on the output file but otherwise ignored. Any line may begin with a colon, in which case the entire line is treated as a comment. Continuation lines are not possible.

Command Summary

CHANGE, VAR=VALUE [, VAR=VALUE, VAR=VALUE ...]

Changes the attribute denoted by VAR to VALUE. Any number of VAR=VALUE sequences may be given in a single command. VAR must be an attribute of an object known to the model (SUCSIM Objects and their attributes are listed later in this routine). Although all attribute values are stored in real format, VALUE may be given in integer, real or exponential notation. If a syntax or other error is discovered, it is noted and the remainder of the command is ignored. In the second example below, X2(1) would not be set, since junk is not a known attribute of any object.

```
CHANGE, X1(1)=4,X2(1)=4.E7
C,X1(1)=22, JUNK=44, X2(1)=44.5
```

END

ENDS THE SIMULATION RUN IMMEDIATELY.

HARVEST,N,S [,VAR2=VAL1, VAL2] [,VAR2=VAL3, VAL4] ...

Harvests (kills) N trees of species S, with or without deadwood production. If N is positive, deadwood is produced as species attributes X10 and X11; if N is negative, no deadwood is produced. Examples

```
HARVEST,6,1    : KILL 6 TREES OF SPECIES 1, WITH DEADWOOD
HARVEST,-6,1   : KILL 6 TREES OF SPECIES 1, NO DEADWOOD
```

The command will not try to kill more trees than actually exist, so to kill all trees of a particular species, a very high tree count may be given.

Up to five attribute criteria may optionally be supplied (only cohort attributes may be specified):

H,6,1,X2=30,50	: KILL UP TO 6 TREES OF SPECIES 1 HAVING A HEIGHT BETWEEN 30 AND 50 CM, INCLUSIVE.
H,6,1,X2=30,50, X3=100,9999999	: KILL UP TO 6 TREES OF SPECIES 1 HAVING A HEIGHT BETWEEN 30 AND 50 CM **AND** TOTAL LEAF BIOMASS OF 100 KG OR MORE.
H,6,1,ID=1,1	: SINCE ID IS A COHORT CRITERION, IT MAY BE USED TO SPECIFY THAT TREES BE KILLED IN A SINGLE COHORT. NORMALLY ALL COHORTS ARE EXAMINED AS LIKELY CANDIDATES UNTIL THE TREE COUNT IS SATISFIED OR ALL COHORTS HAVE BEEN EXAMINED.

LIST,VAR [,VAR] [,VAR] ...

Lists the values of the named attributes or objects on the output file and at the terminal (if running under INTERCOM). Up to ten names may be included in a single command. If a syntax or other error is encountered, the error is noted and the remainder of the command is ignored. There are several possibilities for the types of names that may be specified

ALL	-Specifying L,ALL lists the values of all attributes of all objects currently known to the model. This can get quite lengthy.
OBJ	-(Where OBJ is a valid object name) Lists the values of all attributes of all known objects of the named type (e.g., L,COHORT lists the values of all attributes of all current cohorts).
OBJ(ID)	-(Where ID is the ID number of a current object of type OBJ) lists the values of all attributes of the specified object (e.g., L,SPECIES(2) lists all attributes of species 2).

ATTR -(Where ATTR is a valid attribute name) lists the values of the named attribute for all objects containing that attribute, including, in the case of static objects (all but type COHORT), currently uninitialized objects (e.g., L,B15 lists the values of B15 for all species for which space is currently reserved in the model, regardless of how many species are currently in the model).

ATTR(ID) -(Where ID is the ID number of an object containing attribute ATTR) lists the value of the named attribute in the specified object (e.g., L,X2(1) or L,DTMTR which produces a single output value).

MONITOR [,VAR] [,VAR] ...

Clears or adds to the current monitor request list. Monitor allows several attributes to be monitored at the terminal while the model is running. (The maximum number of monitors is dependent upon terminal screen width; a wide terminal can monitor more attributes than a standard terminal. The maximum for the terminal from which SUCSIM is called is reported to terminal when the program is invoked.) Entering monitor without parameters clears the current request list. Used with attribute name parameters, the current request list is expanded to include the named attributes. Each attribute specification must be single-valued; M,SPECIES and M,X2 are illegal, since each is a multiple-valued reference; M,X5 and M,X2(1) are okay since each has a single value). If a syntax or other error is encountered, the error is noted and the remainder of the command ignored.

Monitor acts in conjunction with the global switch commands ON and OFF (see below).

ON [,SWNAME] [,SWNAME] ...

OFF [,SWNAME] [,SWNAME] ...

Several global switches are available to control various aspects of the model run. Entering ON or OFF without parameters lists the current values of switches; specifying switch names turns the named switches ON or OFF. As many switches as desired may be specified in a single command. If a syntax or other error is encountered, the error is noted and the remainder of the command ignored. Currently-implemented switches and their effects on processing are given below:

ECHO	-(Default off) command files read with the READ and REREAD commands are listed at the terminal only if ECHO is on. If an error is encountered on an external file while ECHO is off, the command is listed at the terminal, followed by the error message, regardless of the switch setting. Also, commands read from a file are always listed on the output file.
DUMP	-(Default off) turn on to enable the writing of binary dumps to file DUMP. Run attribute TDMP is incremented by DTDMP even while the switch is off. (Subroutine DMPP is currently dummied.)
MONITOR	-(Default on) turn off to temporarily defeat the monitor request list. When the switch is turned back on, the request list is again in effect and is intact. (The monitor request list may be manipulated with the MONITOR command while the switch is off, but the revised list won't execute until the switch is turned back on.) Run attribute TMTR is incremented by DTMTR even while the switch is off.
PRINT	-(Default on) turn off to temporarily defeat the print request list. The above rules for the monitor request list apply also to the print request list.
LITTER	-(Default on) turn off to disable the litter submodel. (All litter-related attributes are zeroed each DT.)
DEATH	-(Default on) turn off to disable the mortality submodel. (All mortality-related attributes are zeroed each DT.)
BROWSE	-(Default on) turn off to disable the browsing submodel. (All browse-related attributes are zeroed each DT.)
SEED	-(Default on) turn off to disable the establishment submodel. (All establishment-related attributes are zeroed each DT.)
ZINPUT	-(Default off) turn on to enable new driving variables to be read from file ZINPUT each DTZ. (Subroutine READZ is currently dummied.)

PLANT,N,S [,H] .

Establishes a new cohort of population N and species S and height H (cohort attribute X2). If H is not supplied, 3 cm is used. (X2 for the cohort is actually set to -3 or -H to indicate a new cohort in need of initialization.)

PRINT [,VAR] [,VAR] ...

Clears or adds to the current print request list. Any of the request list possibilities given in the description of the LIST command above may be used with the PRINT command. While the LIST command generates both terminal and output file output, PRINT (under control of the print switch and run attributes TPR and DTPR) writes only to file OUTPUT. It is used to provide a printable tabular summary of the progress of the model run. Note: When the PRINT command is used to add to the current print request list, no check is made to determine if the new item is already on the list. PRINT,ALL,ALL,ALL is legal, but would generate an impossible amount of scratch paper. The maximum number of entries in the print request table is currently limited to 30. PRINT,ALL and PRINT,COHORT each generate a single entry.

READ,FNAME

REREAD,FNAME

Transfers control to file FNAME, from which subsequent commands will be read until end-of-record. REREAD causes the file to be rewound before reading begins, READ does not; thus several command files can be combined onto a single file, separated by ends-of-record (level 1), and executed sequentially. REREAD is used most often, however, to insure that the command file is properly rewound. The external file may contain any combination of commands, including other READ or REREAD commands. When a READ is encountered on an external file, reading from the original file is suspended while the new file is READ; when end-of-record is encountered on the new file, control reverts to the original file. READ and REREAD may be nested to any depth. Commands read from external files are echoed to the terminal only if the echo switch is on (see above).

RUN [,NYRS]

Runs the model. If NYRS is 0 or not supplied, only object-housekeeping-type calculations are performed (subroutine INITB is called to recalculate computed parameters, INITX is called to initialize new cohorts, and CLEANUP is called to deal with zero-population cohorts). If NYRS is supplied, the above calculations are performed--then the model is run for NYRS years.

TIME

Reports the amount of central processor time used so far in the run to the terminal and the output file.

The RUN Object

Timing variables and object counters are available as attributes of the run object, and may be referenced by the LIST, PRINT, CHANGE and MONITOR commands as are any other attributes. All are listed below. They should be well understood before they are indiscriminantly changed in the course of a run.

T	-Current simulation time. This should never be changed during a run. Setting T=0 will not reset the model.
DT	-(Default 1) simulation time increment.
TMTR	-(Default 1) time for the next satisfaction of the monitor request list, at which time it is incremented by DTMTR. May be set to the time at which monitoring is to begin.
DTMTR	-(Default 1) TMTR increment. May be freely changed.
TPR	-(Default 1) Analogous to TMTR; applies to print request list.
DTPR	-(Default 1) TPR increment. May be freely changed.
TZ	-(Default 1) Analogous to TMTR; applies to driving variable input.
DTZ	-(Default 1) TZ increment. May be freely changed.
TDMP	-(Default 1) Analogous to TMTR; applies to binary dump write.
DTDMP	-(Default 1) TDMP increment. May be cautiously changed (a program to read the dump file may depend on constant dump intervals).
NXXXX	-Where XXXX is the first four letters of an object type name (NCOHO, NSPEC, NSTRA, NCELL, NRUN). All default to 0, except NRUN, which is 1. NCOHO should never be set by the user, nor should NRUN. NSPEC, NSTRA, and NCELL must be set by the user before the model will run. All have limits imposed by the current array sizes (NSPEC,6 -- NSTRA,20 -- NCELL,1), and care must be taken to insure that required attribute data exists for each declared object.

RUN ATTRIBUTES MUST BE CAREFULLY MANIPULATED; NO PROTECTIONS EXIST AGAINST THEIR MISUSE.

SECTION B

LIST OF QUANTITIES USED IN SUCSIM IV

B.1

LIST OF INDEXES

Index	Range	Explanation
I	$1 \leq I \leq ncoho$	Cohort index
J	$1 \leq J \leq nspec$	Species index
R	$1 \leq R \leq top + 1$	Stratum index, counting from bottom
ncoho		Number of cohorts
nspec		Number of species

B.2

LIST OF STATE VARIABLES

Name	Units	Explanation
$X_1(I)$	cm	Basal diameter, at ground level, inside bark, tree in cohort I.
$X_2(I)$	cm	Height, tree in cohort I.
$X_3(I)$	kg	Total leaf biomass, tree in cohort I.
$X_4(I)$	yrs	Age of trees in cohort I.
X_5	(none)	Total population of trees in the cell (the sum of the cohort populations).
$X_6(I)$	cm	Diameter of tree in cohort I at breast height (137 cm),inside bark.
$X_7(I)$	none	Species of trees in cohort I.
$X_8(I)$	trees	Number of trees in cohort I.
$X_9(I)$	kg	Mass of bole of a tree in cohort I.
$X_{10}(J)$	kg	Total dead leaf biomass of spp J on cell.
$X_{11}(J)$	kg	Total dead wood biomass of spp J on cell.

B.3

LIST OF DRIVING VARIABLES

Name	Units	Explanation
Z_1	(frac. full sun)	Light at top of canopy. (Reed 1978)
Z_2	optimum temperature days	Temperature-Growth index for the year. (Cleary and Waring 1969)
Z_3	(none)	Moisture availability index: ratio of actual to potential transpiration at end of growing season. (Reed and Waring 1974)

B.4

LIST OF INTERMEDIATE FUNCTIONS

Function	Unit	Definition
$G_1(I)$	(cm y^{-1})	Potential basal diameter growth of tree in Cohort I under optimal environment $f(X_1, X_2, X_3)$
$G_2(I)$	(cm y^{-1})	Yearly height increment of tree in Cohort I $f(X_1, G_6)$
$G_3(J)$	(none)	Effect of temperature on diameter growth under otherwise optimal conditions (species J) $f(Z_2)$
$G_4(J)$	(none)	Effect of moisture status on diameter growth under otherwise optimal conditions (species J) $f(Z_3)$
$G_5(I,J)$	(none)	Effect of light on diameter growth under otherwise optimal conditions, tree of species J in Cohort I $f(G_7)$
$G_6(I)$	(cm y^{-1})	Yearly diameter growth as affected by environment, tree in Cohort I $f(G_1, G_3, G_4, G_5)$
$G_7(I)$	(frac.full sun)	Average light "seen" by tree in Cohort I $f(X_2, G_{10})$
G_8		Not used*
$G_9(R)$	(kg cm^{-3})	Leaf biomass density, stratum R $f(X_2, X_3, X_8)$
$G_{10}(R)$	(frac.full sun)	Light at bottom of stratum R $f[G_9, G_{26}, G_{10}(R+1), Z_1]$
G_{11}		Not used
$G_{12}(I)$	(none)	Fraction of trees in Cohort I to be browsed $f(X_2)$
G_{13}		Not used

*Function identifiers from previous versions of SUCSIM that have been deleted from SUCSIM IV are retained but not used. The names of remaining variables are not changed from previous versions.

$G_{14}(II)$	(none)	Fraction of leaf biomass lost by browse, tree in new Cohort *II* $f(X_2)$
$G_{15}(I)$		Not used
$G_{16}(I)$	(kg tree^{-1})	Litterfall from tree in Cohort *I* $f(X_3, G_5, G_{17})$
$G_{17}(I)$	(kg y^{-1})	New leaf production, tree in Cohort *I* $f(X_1, G_6)$
G_{18}		Not used
G_{19}		Not used
G_{20}		Not used
G_{21}		Not used
$G_{22}(I)$	(none)	Fraction of trees in Cohort *I* killed by slow growth $f(X_8, G_6)$
G_{23}		Not used
G_{24}		Not used
G_{25}		Not used
$G_{26}(R)$	(none)	Fraction of total cell area in stratum *R* covered by leaves $f(X_8, G_{28})$
G_{27}		Not used
$G_{28}(I)$	(cm^2)	Ground area covered by tree in Cohort *I* $f(X_1, X_6)$
$G_{29}(I)$	(cm y^{-1})	Yearly diameter growth at breast height, tree in Cohort *I* $f(X_2, G_6)$
G_{30}		Not used
G_{31}		Not used
$G_{32}(J)$	(none)	Seedling potential for species *J* in cell $f(G_3, G_4, G_{10})$

G_{33}		Not used
$G_{34}(J)$	(none)	Number of seedlings of species J introduced into new Cohort II $f(X_5, G_{32})$

B.5

LIST OF PARAMETERS

Parameter	Unit	Definition
$B_1(J)$ (computed)	$(cm^3 kg^{-1} y^{-1})$	Relates tree volume growth to leaf biomε Species J Used in: G_1
$B_2(J)$	(cm)	Maximum diameter, Species J Used in: G_1, G_2, B_1, B_{24}
$B_3(J)$	(cm)	Maximum height, Species J Used in: G_1, G_2, B_1, B_{24}
$B_4(J)$	(none)	Exponent relating tree volume growth to leaf biomass Used in: G_1, B_1
$B_5(J)$	(OTD)	Minimum temperature index for growth, Species J Used in: G_3
$B_6(J)$	(OTD)	Optimal temperature index for growth, Species J Used in: G_3
$B_7(J)$	(OTD)	Maximum temperature index for growth, Species J Used in: G_3
$B_8(J)$	(none)	Minimum moisture stress index for growth, Species J Used in: G_4
$B_9(J)$	(fraction full sun)$^{-1}$	Exponent in the Bertalanffy equation relating growth to light, Species J Used in: G_5, B_{14}
$B_{10}(J)$	(fraction full sun)	Minimum light for Bertalanffy growth equation, Species J Used in: G_5, G_{32}, B_{14}
$B_{11}(R)$	(cm)	Height of bottom of stratum R Used in: G_9, G_{10}
B_{12}	$(cm^2 kg^{-1})$	Light attenuation constant Used in: G_{10}

B_{13}	(cm^2)	Area of cell Used in: X_8, G_{26}, B_{36}
$B_{14}(J)$ (computed)	(fraction full sun)	Value of $G_7(I)$ when $G_5(J) = 0.1$, species J Used in: G_5, B_{15}
$B_{15}(J)$ (computed)	(fraction full sun)$^{-1}$	Exponent relating growth to low light, species J Used in: G_5
$B_{16}(J)$ (computed)	(none)	Leaf biomass browse fraction exponent, species J Used in: G_{14}, B_{31}
$B_{17}(J)$	(kg cm^{-2})	Leaf biomass growth per unit increase in sapwood area, species J Used in: G_{17}, B_{25}
$B_{18}(J)$	(cm^{-1})	Exponent relating probability of mortality to diameter growth, species J Used in: G_{22}
$B_{19}(J)$	(cm)	Cut-off point for slow growth mortality, species J Used in: G_{22}, B_{18}
$B_{20}(J)$ (computed)	($cm^{-B_{22}}$)	Browse probability coefficient, species J Used in: G_{12}
$B_{21}(J)$	(cm)	Maximum height for significant browse, species J Used in: G_{12}, B_{16}, B_{20}
$B_{22}(J)$	(none)	Exponent relating browse probability to height, species J Used in: G_{12}, B_{20}
$B_{23}(J)$	(cm yr^{-1})	Maximum diameter growth under optimal conditions when tree is 137 cm tall, species J Used in: B_1
$B_{24}(J)$ (computed)	(cm)	Optimal diameter when tree is 137 cm tall, species J Used in: B_1, B_{25}, B_{26}
$B_{25}(J)$ (computed	(kg)	Leaf biomass of tree 137 cm tall under optimal conditions, species J Used in: B_1

$B_{26}(J)$ (computed)	(none)	Slope of $G_{28}(I)$ / $X_1(I)$ when $X_2(I)$ = 137 cm, species J Used in: G_{28}
$B_{27}(J)$	(cm)	Maximum crown diameter, species J Used in: G_{28}, B_{26}
$B_{28}(J)$	(cm^{-1})	Coefficient relating crown size to maximum diameter of open grown conifer, species J Used in: G_{28}, B_{26}
$B_{29}(J)$	(cm)	Offset parameter for calculation of maximum diameter of open grown crown, species J Used in: G_{28}, B_{26}
$B_{30}(J)$	(none)	Maximum fraction of total leaf biomass that can be lost as litter, species J Used in: G_{16}
$B_{31}(J)$ (computed)	(none)	Intercept of exponential term in G_{14} when X_2 = 0, species J Used in: G_{14}
$B_{32}(J)$	(cm)	Maximum height for full defoliation due to browse, species J Used in: B_{31}
B_{33}		Not used
$B_{34}(J)$		Threshold probability of population dependent slow growth mortality Used in: G_{22}, B_{39}
$B_{35}(J)$	(cm)	Parameter modifying crown diameter of species J relative to Douglas fir Used in: G_{28}
B_{36} (computed)	(trees)	Maximum number of trees in cell Used in: G_{32}, G_{34}
$B_{37}(J)$	(none)	Seedyear cycle, species J Used in: G_{32}
$B_{38}(J)$	(none)	Maximum probability of browse, species J Used in: B_{20}

$B_{39}(J)$ (computed)	(none)	Slope of probability of population-dependent mortality to population when $X_8(I) < 10$ Used in: G_{22}
$B_{40}(J)$	(none)	Offyear seedling potential Used in: G_{32}
$B_{41}(J)$	(fraction full sun)	Optimum light for establishment, species J Used in: G_{32}
$B_{42}(J)$	(fraction full sun)	Maximum light for establishment, species J Used in: G_{32}
B_{43}	(trees ha^{-1})	Maximum stocking
B_{44}	(trees ha^{-1})	Maximum number of trees killed by random factors Used in: X_8
$B_{45}(J)$	(gm/cm^3)	Bole density, species J Used in: X_9

B.6

SPECIES DEPENDENT PARAMETER VALUES

Param Name	1 D. Fir	2 P. Pine	3 N. Fir	4 G. Fir	5 W. Hem.	6 W.R.C.
B_1	*	*	*	*	*	*
B_2	460	200	250	200	275	560
B_3	11800	7000	7500	7500	7900	7600
B_4	1.145	1.18	1.16	1.16	1.18	1.155
B_5	35	45	30	35	35	35
B_6	75	90	65	75	60	65
B_7	95	110	70	85	75	80
B_8	0.29	0.25	0.7	0.5	0.5	0.7
B_9	5.17	5.83	5.17	4.78	4.78	4.78
B_{10}	0.1	0.2	0.1	0.025	0.025	0.025
B_{14}	*	*	*	*	*	*
B_{15}	*	*	*	*	*	*
B_{17}	0.072	0.043	0.051	0.051	0.074	0.05
B_{18}	*	*	*	*	*	*
B_{19}	0.05	0.01	0.05	0.02	0.006	0.006
B_{20}	*	*	*	*	*	*
B_{21}	150	150	150	150	150	150
B_{22}	0.5	0.5	0.5	0.5	0.5	0.5
B_{23}	1.45	0.6	0.55	0.5	1.0	1.2
B_{24}	*	*	*	*	*	*
B_{25}	*	*	*	*	*	*
B_{26}	*	*	*	*	*	*

SPECIES DEPENDENT PARAMETER VALUES (CONT.)

Param Name	1 D. Fir	2 P. Pine	3 N. Fir	4 G. Fir	5 W. Hem.	6 W.R.C.
B_{27}	2203	2203	2203	2203	2203	2203
B_{28}	0.0136	0.0136	0.0136	0.0136	0.0136	0.0136
B_{29}	4.03	4.03	4.03	4.03	4.03	4.03
B_{30}	0.23	0.33	0.25	0.25	0.25	0.18
B_{31}	*	*	*	*	*	*
B_{32}	30	30	30	30	30	30
B_{34}	0.1	0.1	0.1	0.1	0.1	0.1
B_{35}	1.0	.8	.7	.7	1.0	1.0
B_{37}	9	9	9	9	9	9
B_{38}	0.3	0.35	0.15	0.15	0.15	0.15
B_{39}	*	*	*	*	*	*
B_{40}	.01	.01	.01	.01	.01	.01
B_{41}	0.8	0.9	0.6	0.7	0.6	0.6
B_{42}	0.9	1.1	0.8	0.85	0.7	0.7
B_{45}	0.7	0.7	0.7	0.7	0.7	0.7

B.7

NON-SPECIES SPECIFIC PARAMETER VALUES

Parameter Name	
$B_{11}(R)$	0, 25, 50, 75, 100, 300, 500, 750, 1000, 1500, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, 10000, 12000
B_{12}	17700
B_{13}	1×10^8
B_{43}	2500
B_{44}	10

SECTION C

COMPUTED PARAMETERS

These parameters values are computed from other quantities and are usually evaluated at the beginning of each run.

$B_1(J)$ = Parameter relating tree volume growth to leaf biomass, species J (cm kg^{-1} y^{-1})

$$B_1(J) = \frac{B_{23}(J)\left\{\dfrac{B_3(J)\ B_{24}(J)^2}{B_2(J)}\left[6 - \dfrac{4B_{24}(J)}{B_2(J)}\right]\right\}}{B_{25}(J)^{B_4(J)}\left[1 - \dfrac{137\ B_{24}(J)}{B_2(J)\ B_3(J)}\right]}$$

$B_2(J)$ = Maximum diameter, species J (cm)

$B_3(J)$ = Maximum height, species J (cm)

$B_4(J)$ = Parameter relating volume growth to leaf biomass, species J (dimensionless)

$B_{23}(J)$ = Maximum diameter growth under optimal conditions when tree is 137 cm tall, species J (cm y^{-})

$B_{24}(J)$ = Optimal diameter when tree is 137 cm tall, species J (cm)

$B_{25}(J)$ = Leaf biomass when tree is 137 cm tall grown under optimal conditions, species J (kg)

Comment:
It is derived by solving eq. $G_1(I)$ for $B_1(J)$, substituting $B_{23}(J)$, $B_{24}(J)$, and $B_{25}(J)$ for $G_1(I)$, $X_1(I)$, and $X_3(I)$, respectively.

$B_{14}(J)$ = Value of $G_7(I)$ when $G_5(J)$ = 0.1 (fraction full sun)

Used in: G_5

$$B_{14}(J) = B_{10}(J) + \frac{\ln 1.1}{B_9(J)}$$

$B_9(J)$ = Exponent in the Bertalanffy equation relation growth to light, species J $[G_7(I) > B_{14}]$ (fraction full sun)

$B_{10}(J)$ = Minimum light for Bertalanffy growth equation, species J (fraction full sun

$B_{15}(J)$ = Exponent relating low light to growth computed when $G_7(I) = B_{14}(J)$ and $G_5(J) = 0.1$ (fraction full sun)$^{-1}$

Used in: G_5

$$B_{15}(J) = \frac{ln(100)}{B_{14}(J)}$$

$B_{14}(J)$ = Value of $G_7(I)$ when $G_5(I,J) = 0.1$ (fraction sull sun)

$B_{16}(J)$ = Leaf biomass browse fraction exponent (cm^{-1})

Used in: G_{14}, B_{31}

$$B_{16}(J) = \frac{-ln\ .01}{B_{21}(J)}$$

$B_{21}(J)$ = Maximum height for significant browse, species J (cm)

$B_{18}(J)$ = Parameter relating probability of mortality to diameter growth, species J (cm^{-1})

Used in: G_{22}

$$B_{18}(J) = \frac{-ln\ (0.001)}{B_{19}(J)}$$

$B_{19}(J)$ = Cut-off point for slow growth mortality, species J (cm)

Comment:
$B_{18}(J)$ is calculated from G_{22} such that $G_{22}(I) = 0.001$ for $G_6(I) = B_{19}(J)$.

$B_{20}(J)$ = Browse probability coefficient, species J ($cm^{-B_{22}}$).

Used in: G_{12}

$$B_{20}(J) = \frac{B_{38}(J)}{B_{21}(J)^{B_{22}(J)}}$$

$B_{38}(J)$ = Maximum probability of browse, species J (dimensionless)

$B_{21}(J)$ = Maximum height for significant browse, species J (cm)

$B_{22}(J)$ = Exponent relating browse probability to height, species J (dimensionless)

$B_{24}(J)$ = Optimal diameter when tree is 137 cm tall, species J (cm)

Used in: B_1, B_{25}, B_{26}

$$B_{24}(J) = \mathrm{DIAM}(a,b,c)$$

$$a = \frac{B_3(J)}{B_2(J)^2}$$

$$b = \frac{2\ B_3(J)}{B_2(J)}$$

$$c = 137$$

$B_2(J)$ = Maximum diameter, species J (cm)

$B_3(J)$ = Maximum height, species J (cm)

DIAM = Function to solve quadradic equation

$B_{25}(J)$ = Leaf biomass of tree 137 cm tall grown under optimal conditions, species J (kg)

Used in: B_1

$$B_{25}(J) = \frac{\pi}{4} [B_{17}(J)\ B_{24}(J)^2]$$

$B_{17}(J)$ = Leaf biomass growth per unit increase in sapwood area, species J (kg cm^{-2})

$B_{24}(J)$ = Optimal diameter when tree is 137 cm tall, species J (cm)

$B_{26}(J)$ = Slope of G_{28}/X_1 when $G_2 < 137$ (dimensionless)

Used in: G_{28}

$$B_{26}(J) = \frac{B_{27}(J)}{B_{24}(J)} \left\{1 - \exp\left[-B_{28}(J)\ B_{29}(J)\right]\right\}$$

$B_{24}(J)$ = Basal diameter of a tree of species J when $G(I) = 137$ (cm)

$B_{27}(J)$ = Maximum crown diameter, species J (cm)

$B_{28}(J)$ = Coefficient relating crown size to maximum diameter, species J (cm^{-1})

$B_{29}(J)$ = Offset parameter, species J (cm)

$B_{31}(J)$ = Intercept of exponential term of $G_{14}(I)$ when $X_2(I) = 0$;

such that $G_{14}(I) = 1$ when $X_2(I) = B_{32}(J)$

Used in: G_{14}

$$B_{31}(J) = \frac{1}{\exp\,[-B_{16}(J)\;B_{32}(J)]}$$

$B_{16}(J)$ = Leaf biomass browse fraction exponent (computed))(cm^{-1})

$B_{32}(J)$ = Maximum height for full defoliation due to browse (cm)

B_{36} = Maximum number of trees in cell

$$B_{36} = \frac{B_{43}\ B_{13}}{10^8}$$

B_{13} = Area of cell (cm^2)

B_{43} = Maximum tree population density (trees ha^{-1})

$B_{39}(J)$ = Slope of probability of population dependent mortality to population when $X_8(I) < 10$

$$B_{39}(J) = \frac{1 - B_{34}(J)}{10}$$

$B_{34}(J)$ = Threshold probability for population-dependent slow growth mortality (dimensionless)

SECTION D

UTILITY FUNCTIONS

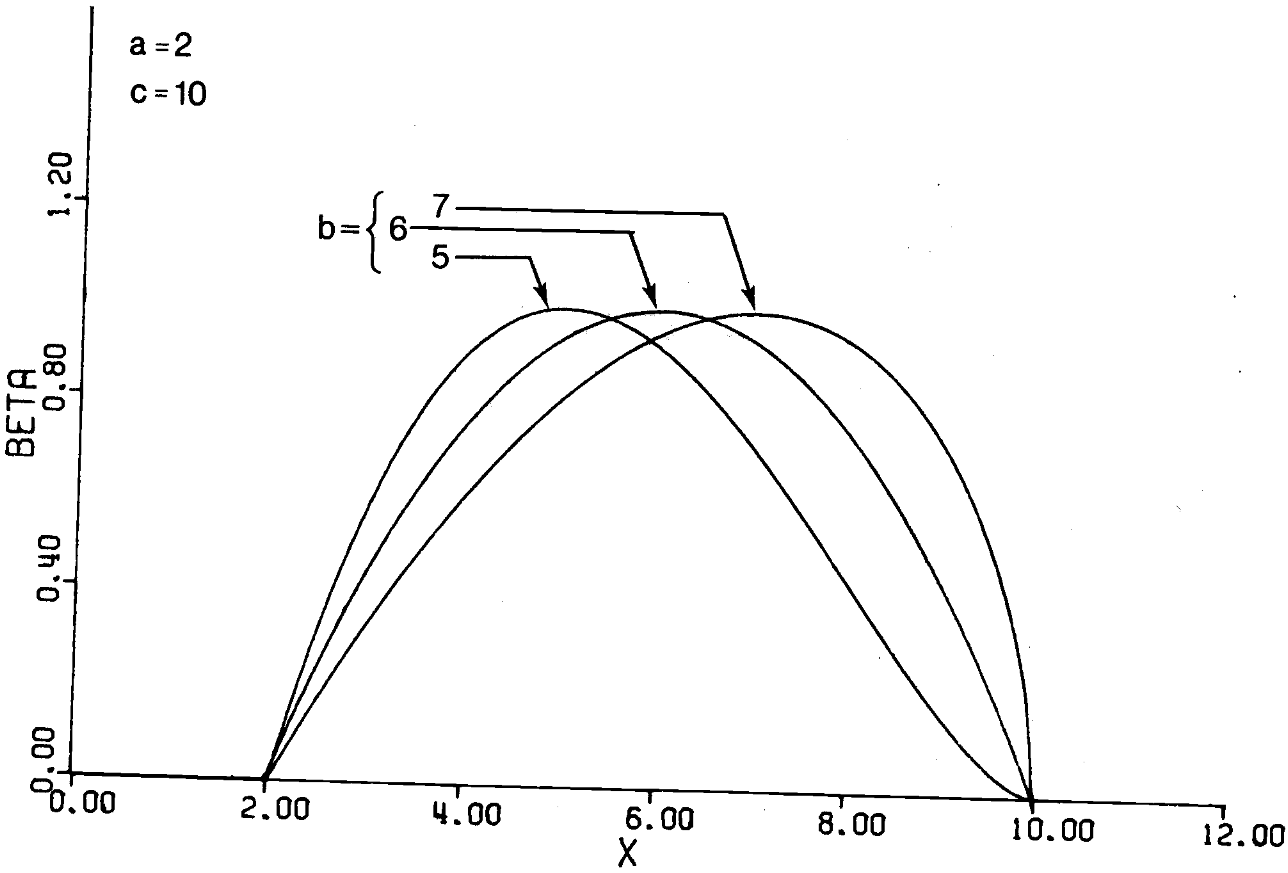
β = Beta function

$$B(a, b, c, x) = \begin{cases} \dfrac{(x-a)(c-x)^{v}}{(b-a)(c-b)^{v}} & \text{If } X \varepsilon (a, c) \\ 0 & \text{Otherwise} \end{cases}$$

$$v = \frac{c - b}{b - a}$$

Comment:

MAX [$\beta(a, b, c, x)$] = 1
a, b, c, x are arguments passed into function β



DIAM = Function to solve for smallest non-negative root of a quadradic equation.

$$\text{DIAM}\ (a,\ b,\ c) = \text{MAX}\left[\frac{-b - \sqrt{T_1}}{2a},\ 0\right]$$

$$T_1 = \text{MAX}\ [(b^2 - 4ac),\ 0]$$

---

a, b, c are arguments passed into function DIAM

SECTION E

DOCUMENTATION OF SUCSIM MODELS

The models are grouped into modules corresponding to the SUCSIM IV processes. The documentation of each module includes a flow diagram. Quantities passed into the module of interest from another module are indicated by placement above a dashed line. Solid symbols indicate values computed during current iteration, broken symbols are quantities computed in the previous iteration. State variables (X's) are symbolized by boxes, intermediate variables (G's) by circles, driving variables (Z's) by diamonds. The modules are presented in the order of execution after initialization (parameters and state variables are initialized at year 0).

E.1 INITIALIZATION OF STATE VARIABLES

$X_1(I) = \text{DIAM}\,[a,\ b,\ X_2(I)]$

$$a = \frac{B_3(J)}{B_2(J)^2}$$; $B_3(J)$ = Maximum height of species J
; $B_2(J)$ = Maximum diameter of species J

$$b = -\frac{2\ B_3(J)}{B_2(J)}$$

$$X_2(I) = \begin{cases} 3 & \text{if SEEDED} \\ \text{user selectable} & \text{if planted} \end{cases}$$

$X_3(I) = B_{17}(J)\ X_1(I)$; $B_{17}(J)$ = leaf biomass growth per unit increase in sapwood area, species J

$X_4(I) = 0$

$$X_5 = \sum_{I=1}^{ncoho} X_8(I)$$

$X_6(I) = 0$

$X_7(I) = J$; user selectable species index, $J \in (1,\ 6)$

$X_8(I)$ = user selectable cohort population, $X_8(I) \in (1,\ B_{36})$
B_{36} = Maximum population of cell

$X_9(I),\ X_{10}(I),\ X_{11}(I) = 0$

Comments:
State variables are initialized after initialization of the computed parameters. Refer to section B.2 for identification of state variables.

E.2 THE LIGHT MODULE

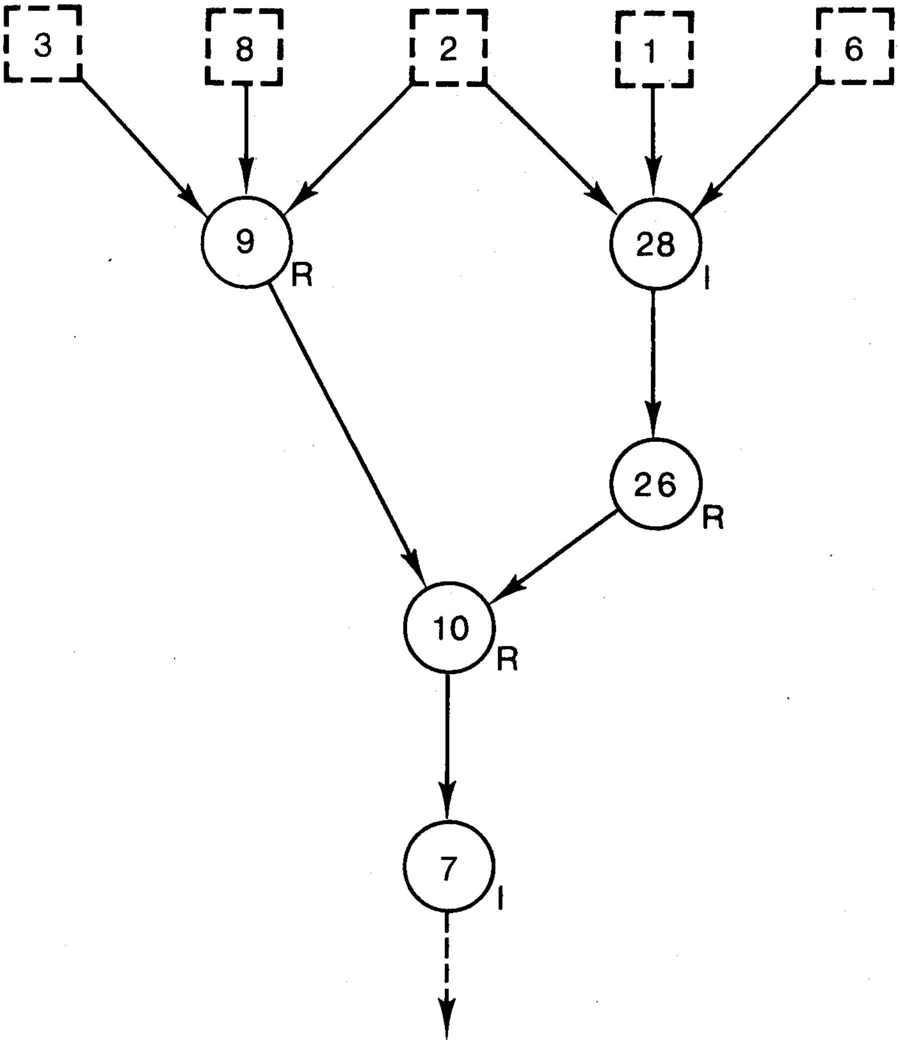
This module is based on the assumption that light is attenuated exponentially through a conifer stand (Reifsnyder et al., 1971/72). The canopy is divided into numerous strata, through which light is attenuated as a function of leaf biomass density. The light extiction coefficient, B_{12} was estimated by assuming that a very dense conifer stand would let only 1% full sun to the forest floor (20 tons per hectare). Future plans include estimates of B_{12} under stands of different species, as well as mixed conifer stands.

The model requires average light intercepted by the trees in each cohort. We assume at this time that light is attenuated as a simple exponential function of leaf biomass after Monsi & Saeki (1953) and Reifsnyder et al., (1971/72). For simplicity, we assume a uniform vertical distribution of leaf biomass around each tree, and that if the stand is not closed, some of the light incident on the top of the canopy falls to the ground unattenuated. All trees receive some of this unattenuated light.

Because the canopy is divided into strata, we must compute the amount of light at each level in the canopy. The basic relation is:

$$I_R = I_{R+1} \left[A_R \exp\left(-k \, \rho_R \, \Delta z\right) + \left(1 - A_R\right)\right]$$

Where I_R is light at any level R, I_{R+1} is light at top of the stratum, A_R is the ratio of cell area covered by leaves to the total cell area, k is the attenuation constant, ρ_R is the density of leaf biomass in the stratum and z is the depth of the stratum. This relation allows us to compute insolation at any level in the stand. Average light "seen" by each tree is simply the sum of the average light in each stratum of which the tree is a component.



LIGHT MODULE

$G_7(I)$ = Average light seen by tree in Cohort I (fraction full sun)

$$G_7(I) = \sum_{R=1}^{R(top)} T_1 \, T_2$$

$$T_1 = [G_{10}(R+1) + G_{10}(R)] \,/\, 2$$

$$T_2 = \left\{ \text{Min}\, [X_2(I),\, B_{11}(R+1)] - B_{11}(R) \right\} / \, X_2(I)$$

T_1 = Average light in stratum R (fraction full sun)

T_2 = Proportion of tree in stratum R

$X_2(I)$ = Height of tree in Cohort I

$G_{10}(R)$ = Light at bottom of stratum R (fraction full sum)

$B_{11}(R)$ = Height of bottom of stratum R (cm)

$R(top)$ = Stratum occupied by the top of tree in Cohort I

G_9 = Leaf biomass density, stratum R (kg cm^{-3})

$$G_9(R) = \sum_{I=1}^{ncoho} \frac{[X_8(I)\ X_3(I)\ T_1]}{[X_2(I)\ T_2]}$$

$$T_1 = \text{Min}\ [X_2(I),\ B_{11}(R+1)] - B_{11}(R)$$

$$T_2 = B_{13}\ [B_{11}(R+1) - B_{11}(R)]$$

T_1 = Vertical fraction of tree in stratum

T_2 = Cell volume of stratum (cm^3)

$X_2(I)$ = Height of tree in Cohort I (cm)

$X_3(I)$ = Leaf biomass of tree in Cohort I (kg)

$X_8(I)$ = Population of Cohort I

$B_{11}(R)$ = Height of bottom of stratum R (cm)

$G_{10}(R)$ = Light at bottom of stratum R (fraction full sum)

$$G_{10}(R) = \begin{cases} Z_1 & ; \text{ If } G_{10}(R+1) = Z_1 \text{ and } G_9(R) = 0 \\ G_{10}(R+1)\left\{G_{26}(R)\, T_1 + [1 - G_{26}(R)]\right\}; & \text{otherwise} \end{cases}$$

$$T_1 = \exp\left\{-B_{12}G_9(R)\,[B_{11}(R+1) - B_{11}(R)]\right\}$$

T_1 = Attenuation of light by leaf biomass density in stratum R

$G_9(R)$ = Density of leaf biomass in stratum R (kg cm^{-3})

$G_{26}(R)$ = Fraction of cell area occluded by leaves

$B_{11}(R)$ = Height at bottom of stratum R (cm)

B_{12}= Light attenuation constant (cm^2 kg^{-1})

$G_{26}(R)$ = Fraction of cell area in stratum R covered by leaves

$$G_{26}(R) = \text{Min}\left[1, \frac{T_1}{B_{13}}\right]$$

$$T_1 = \sum_{I=1}^{ncoho} G_{28}(I)\ X_8(I)$$

T_1 = Plot area covered by all trees in Cohort I (cm)

$X_8(I)$ = Population of Cohort I

$G_{28}(I)$ = Ground area covered by tree in Cohort I

B_{13} = Area of cell (cm^2)

$ncoho$ = Number of cohorts in stand

$G_{28}(I)$ = Ground area of tree in Cohort I (cm)

$$G_{28}(I) = \begin{cases} \frac{\pi}{4} B_{35}(J)\ T_1^2 & ;\ X_2(I) < 137 \text{ cm} \\ \frac{\pi}{4} B_{35}(J)\ T_2^2 & ;\ \text{Otherwise} \end{cases}$$

$$T_1 = B_{26}(J)\ X_1(I)$$

$$T_2 = B_{27}(J) \left\{ 1 - \exp\left[-B_{28}(J)[X_6(I) + B_{29}(J)] \right] \right\}$$

T_1, T_2 = Open-grown crown diameter of tree in Cohort I (cm) of height $X_2(I)$ (cm)

$X_1(I)$ = Basal diameter of tree in Cohort I (cm)

$X_6(I)$ = Diameter at breast height (137 cm) of tree in Cohort I (cm)

$B_{26}(J)$ = Slope of $G_{28}(I)$ / $X_1(I)$ when $X_2(I)$ = 137 cm, species J (dimensionless)

$B_{27}(J)$ = Maximum crown diameter, species J (cm)

$B_{28}(J)$ = Coefficient relating crown size to maximum diameter of open-grown conifer, species J (cm^{-1})

$B_{29}(J)$ = Offset parameter for calculation of maximum diameter of open-grown conifer crown, species J (cm)

$B_{35}(J)$ = Parameter relating crown diameter of species J to Douglas fir (dimensionless)

Comment:
Derivation on next page.

DERIVATION OF $G_{28}(I)$

Arney (1972) measured crown width of numerour open-grown Douglas fir and by regression analysis developed the relation:

$$\text{Crown width (ft)} = \beta_0 + \beta_1 \text{DBH} - \beta_2 \text{DBH}^2 = 4.56 + 2.04\ \text{DBH} - 0.0191\ \text{DB}$$

But this curvilinear function is estimated from data from trees of less than 1.2 m DBH. Consequently, the function reached a maximum ($dy/dx = 0$) when DBH = 53.4" (1.35 m). We created a new data set using Arney's equation and converting to centimeters:

DBH (cm)	Crown DIA (cm)
0	139.3
12.7	435.9
25.4	704.1
38.1	941.8
50.8	1149.1
63.5	1332.0
76.2	1481.3
88.9	1603.2
101.6	1697.7
127.0	1792.8

We fitted the non-linear model

$$y = \beta_1\{1 - \exp[-\beta_2(X + \beta_3)]\}$$

to the data set by non-linear least squares where

$\beta_1 = 2203.4$
$\beta_2 = 0.0136$
$\beta_3 = 4.03$
X = DBH

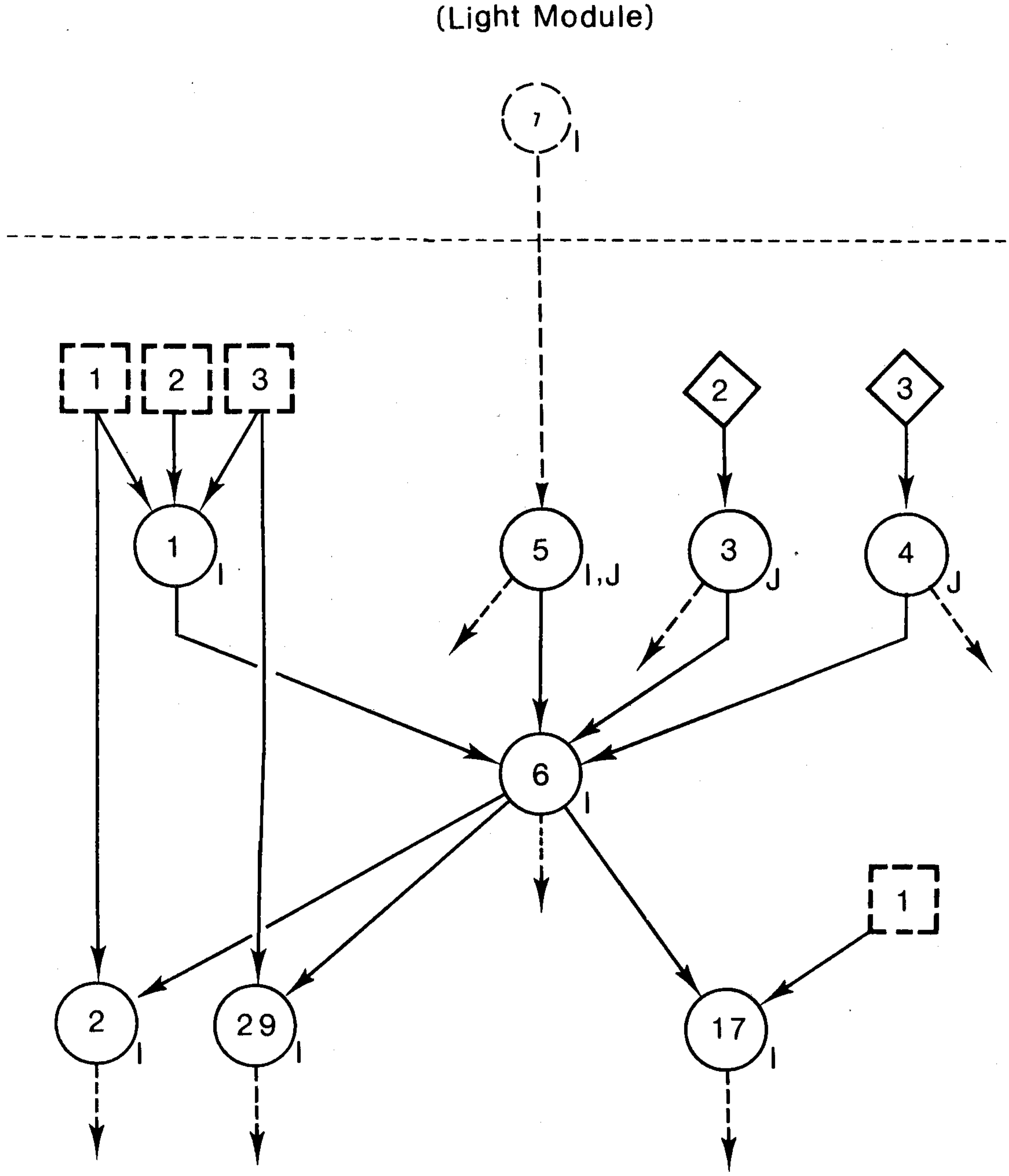
The non-linear function was virtually indistinguishable from the linear equation used by Arney, but has the advantage of becoming asymptotic to some maximum value of X, rather than decreasing from the maximum as does the parabolic function.

E.3 THE GROWTH MODULE

The growth module is the most complex of the current SUCSIM IV models. The primary purpose is to produce basal diameter increment from which height, leaf biomass and DBH increments are computed. The model assumes a cone-shaped bole, basal diameter (X_1) is an imaginary extension of the cone to the ground, ignoring "butt swell". Diameter growth at breast height (G_{29}) is assumed to be equal to basal diameter growth, once the tree reaches 137 cm in height. Potential diameter growth is computed, then that growth is modified by the set of environmental functions that reflect the effect of light, temperature and moisture on growth.

Future work includes development of a more realistic height-growth model, conversion from leaf biomass to leaf area, and an improved crown shape model. Data for estimation of parameters are being processed. The data are courtesy of W.H. Emmingham, R.H. Waring and others.

The growth model, its derivation and ecological significance are discussed in Reed (1978).



GROWTH MODULE

$\dot{G}_1(I)$ = Potential basal diameter growth of tree in Cohort I (cm kg^{-1}) under optimal environment

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$$G_1(I) = T_1 \;/\; T_3$$

$$T_1 = B_1(J)\; X_3(I)^{B_4(J)}\; T_2$$

$$T_2 = 1 - \frac{X_1(I)\; X_2(I)}{B_2(J)\; B_3(J)}$$

$$T_3 = \frac{B_3(J)\; X_1(I)}{B_2(J)} \left[6 - \frac{4X_1(I)}{B_2(J)}\right]$$

T_1 = Effect of leaf biomass on diameter growth

T_2 = Effect of size (respiration) on growth

T_3 = Denominator, relating diameter growth to volume growth

$X_1(I)$ = Basal diameter of tree in Cohort I (cm)

$X_2(I)$ = Height of tree in Cohort I (cm)

$X_3(I)$ = Leaf biomass of tree in Cohort I (kg)

$B_1(J)$ = Coefficient relating volume growth to leaf biomass, species J (cm kg^{-1}y^{-1})

$B_2(J)$ = Maximum diameter, species J (cm)

$B_3(J)$ = Maximum height, species J (cm)

$B_4(J)$ = Exponent relating volume growth to leaf biomass, species J (dimensionless)

Comment:
Derivation on next page.

DERIVATION OF G_1

Botkin et al. (1972) developed an individual tree growth model that assumed that volume growth is related linearly to leaf biomass. They then defined leaf biomass in terms of DBH; the resulting expression when solved over time gave a hyperbolic curve form. We require an explicit expression of growth to leaf biomass, and diameter growth from ground up, not from breast height. Therefore, we assumed that volume growth increase is proportional to a non-linear leaf biomass term. However, as the tree grows, progressively more energy is diverted to maintenance, causing growth reduction. Botkin et al. assumed that when maintenance respiration equals photosynthesis, growth stops. Our resulting basic equation is:

$$\delta v = \frac{dv}{dt} = b_1 W^{b_4} \; (1 - DH/D_m H_m) \qquad (1)$$

which reduces to

$$\delta v = P - R = \text{Photosynthesis-Respiration}$$

where

$$P = b_1 W^{b_4} \text{ and } R = b_1 W^{b_4} \; DH/D_m H_m$$

and

H = height (cm)
D = diameter
D_m = maximum diameter
H_m = maximum height
W = leaf biomass
b_1, b_4 are parameters

Let $\delta(v) = \delta(D^2\, H)$, then volume growth is given by:

$$\delta(D^2\, H) = b_1 W^{b_4} \; (1 - DH/D_m H_m) \qquad (2)$$

Let

$$H = aD - \beta D^2 \qquad (3)$$

where

$$a = 2\, H_m\, D_m^{-1} \text{ (dimensionless)}$$

$$\beta = H_m\, D_m^{-2} \qquad (\text{cm}^{-1})$$

Substituting eq. (2) into eq. (1) gives

$$\delta(aD^3 - \beta D^4) = b_1 W^{b^4} \; (1 - DH/D_m H_m)$$

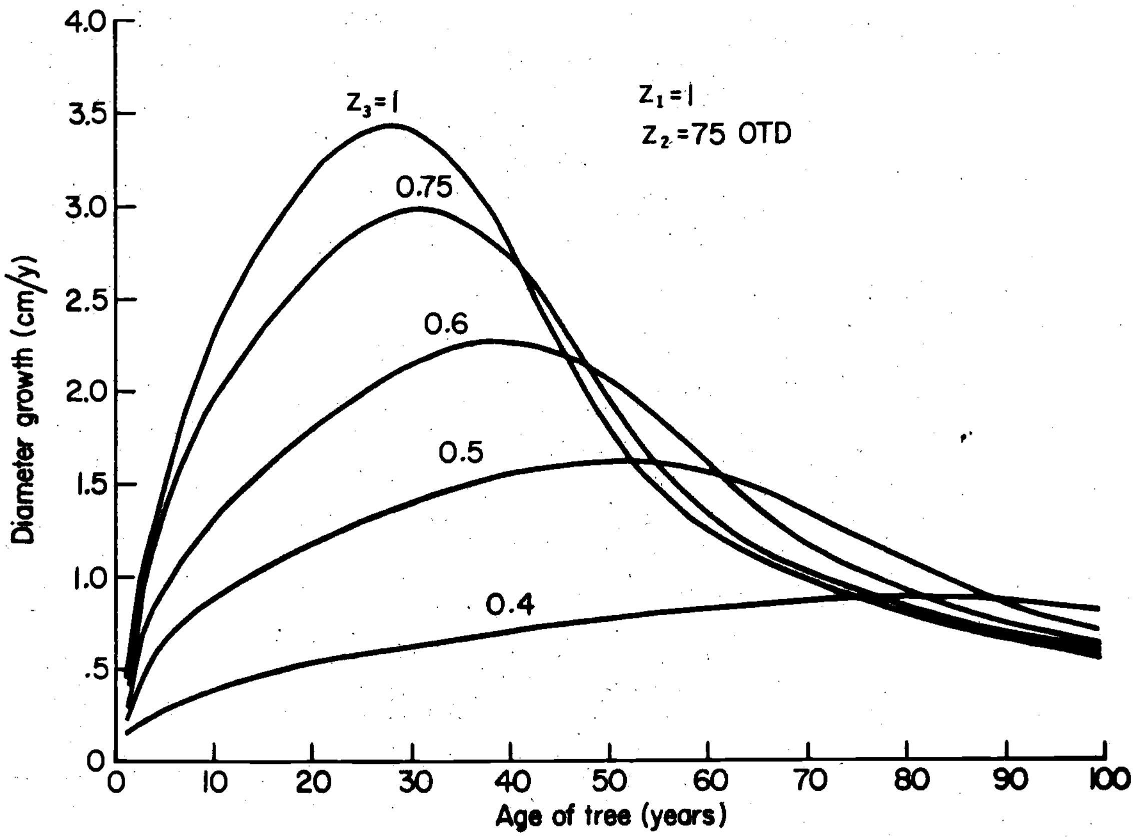
By implicit differentiation:

$$\delta D(3aD^2 - 4\beta D^3) = b_1 W^{b_4} (1 - DH\ D_m H_m)$$

$$\delta D = \frac{b_1 W^{b_4} (1 - DH/D_m H_m)}{3aD^2 - 4\beta D^3} = G_1(J)$$

or

$$G_1(J) = \frac{B_1(J)\ X_3(I)^{B_4(J)}\ [1 - (X_1(J)\ G_2(I)\ /\ B_2(J)\ B_3(J))]}{\dfrac{6B_3(J)}{B_2(J)}\ X_1(J)^2 - \dfrac{4B_3(J)}{B_2(J)^2}\ X_1(J)^3}$$



$G_2(I)$ = Yearly height increment for tree in Cohort I (cm y^{-1})

$$G_2(I) = \frac{2B_3(J)\ G_6(I)}{B_2(J)} \left[1 - \frac{X_1(I)}{B_2(J)}\right]$$

$B_2(J)$ = Maximum diameter of species J (cm)

$B_3(J)$ = Maximum height of species J (cm)

$X_1(I)$ = Basal diameter growth of Tree I current year (cm y^{-1})

$G_6(I)$ = Basal diameter of Tree I (cm)

Comment:
Derivation next page.

DERIVATION OF $G_2(I)$

Assuming that height H is proportional to diameter D, (Botkin et al. 1972), let

$$H = \alpha D - \beta D^2 \quad (1)$$

where

$\alpha = 2H_m D_m^{-1}$ (dimensionless)
$\beta = H_m D_m^{-2}$ (cm^{-1})
H_m = Maximum height, species specific
D_m = Maximum diameter, species specific

Differentiation of (1) gives

$$dH = (\alpha - 2\beta D)dD$$

or

$$dH = (2H_m D_m^{-1} - 2H_m D_m^{-2} D)dD$$

which can be approximated by

$$\Delta H = (2H_m D_m^{-1} - 2H_m D_m^{-2} D)\Delta D$$

Letting $D_m = B_2(J)$ and $H_m = B_3(J)$, substitution and rearrangement gives:

$$G_2(I) = \Delta H = \frac{2G_6(I)\ B_3(J)}{B_2(J)} \left[1 - \frac{X_1(I)}{B_2(J)}\right]$$

(where $G_6(I) = \Delta D$)

Total height of Tree I at time t is given by

$$H = X_2(I,t) = \sum_{k=1}^{t} G_2(I,k)$$

$G_3(J)$ = Effect of temperature on diameter growth under otherwise optimal environment, species J (dimensionless)

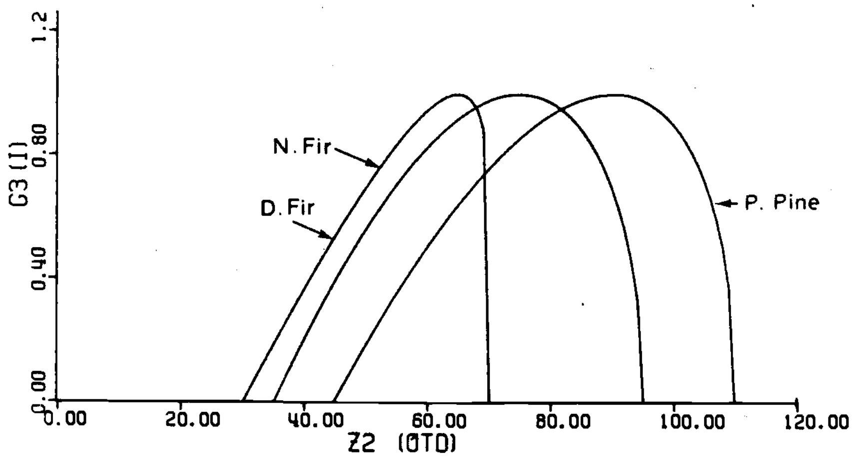
$$G_3(J) = \begin{cases} \beta[B_5(J),\ B_6(J),\ B_7(J),\ Z_2] & ;\ Z_2 \in [B_5(J),\ B_7(J)] \\ 0 & ;\ \text{Otherwise} \end{cases}$$

Z_2 = Temperature index for the year (optimum temperature days)

$B_5(J)$ = Minimum temperature index for growth, species J (optimum temperature days)

$B_6(J)$ = Optimal temperature index for growth, species J (optimum temperature days)

$B_7(J)$ = Maximum temperature index for growth, species J (optimum temperature days)



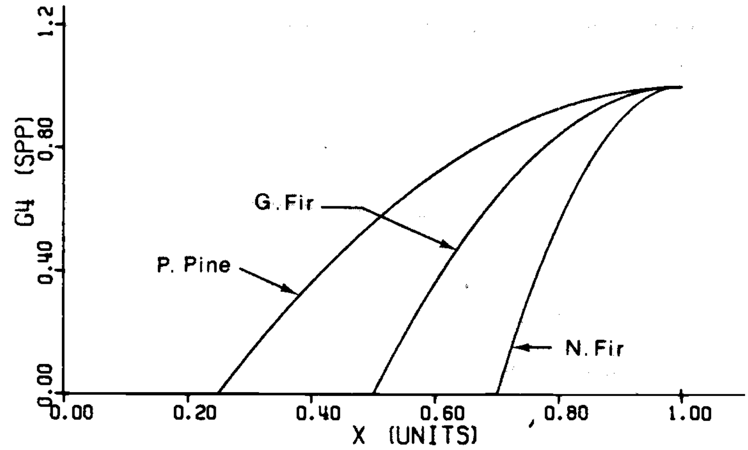
Comment:
Temperature index defined as the temperature growth index (Cleary and Waring, 1969; Reed and Waring, 1974; Zobel <u>et al</u>., 1976), in units: OTD's.

$G_4(J)$ = Effect of moisture on growth under otherwise optimal environment, species J (dimensionless)

$$G_4(J) = \begin{cases} \beta[B_8(J),\ 1,\ 2 - B_8(J),\ Z_3]; & \text{if } Z_3 \in [B_8,\ 1] \\ 0 & ;\ \text{Otherwise} \end{cases}$$

$B_8(J)$ = Minimum moisture stress index for growth, species J (dimensionless)

Z_3 = Moisture stress index for the year (dimensionless)



Comment:
Moisture stress is defined as the ratio of simulated "actual" transpiration to potential (Reed and Waring, 1974).

$G_5(I,J)$ = Effect of light on growth of tree of species J in Cohort I under otherwise optimal environment (dimensionless)

$$G_5(I,J) = \begin{cases} 1 - \exp\{-B_9(J)[G_7(I) - B_{10}(J)]\} & ; G_7(I) \geq B^{14}(J) \\ 10^{-3} \exp[B_{15}(J)\, G_7(I)] & ; \text{Otherwise} \end{cases}$$

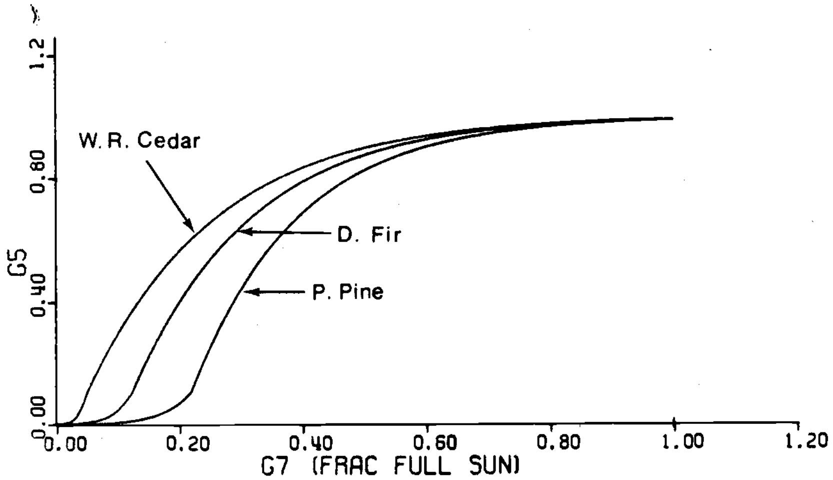
$G_7(I)$ = Average light "seen" by a tree in Cohort I (fraction full sun)

$B_9(J)$ = Exponent in the Bertalanffy equation relating growth to light, species J

$B_{10}(J)$ = Minimum light for Bertalanffy growth equation (fraction full sun)

$B_{14}(J)$ = Value of $G_7(I)$ when $G_5(I,J) = 0.1$

$B_{15}(J)$ = Exponent relating growth to low light (fraction full sun)$^{-1}$



Comment:
The upper expression in G_5 is the von Bertalanffy growth equation.

$G_6(I)$ = Yearly diameter growth as affected by environment, tree in Cohort I (cm)

$$G_6(I) = G_1(I)\ G_3(J)\ G_4(J)\ G_5(I,J)$$

$G_1(I)$ = Maximum potential growth, Tree I (cm)

$G_3(J)$ = Temperature effect on growth, species J (dimensionless) $G_3(J) \in [0,1]$

$G_4(J)$ = Moisture effect on growth, species J (dimensionless) $G_4(J) \in [0,1]$

$G_5(I,J)$ = Light effect on growth, species J in Cohort I (dimensionless) $G_5(I,J) \in [0,1]$

$G_{17}(I)$ = New leaf production of tree in Cohort I (kg y^{-1})

$$G_{17}(I) = B_{17}(J) \frac{\pi}{4} \left\{ [X_1(I) + G_6(I)]^2 - X_1(I)^2 \right\}$$

$X_1(I)$ = Diameter of tree in Cohort I (kg)

$G_6(I)$ = Diameter growth during the year for tree in Cohort I (cm)

$B_{17}(J)$ = Leaf biomass growth per unit increase in sapwood area, species J (kg/cm^2)

$G_{29}(I)$ = Diameter growth at breast height, tree in Cohort I (cm)

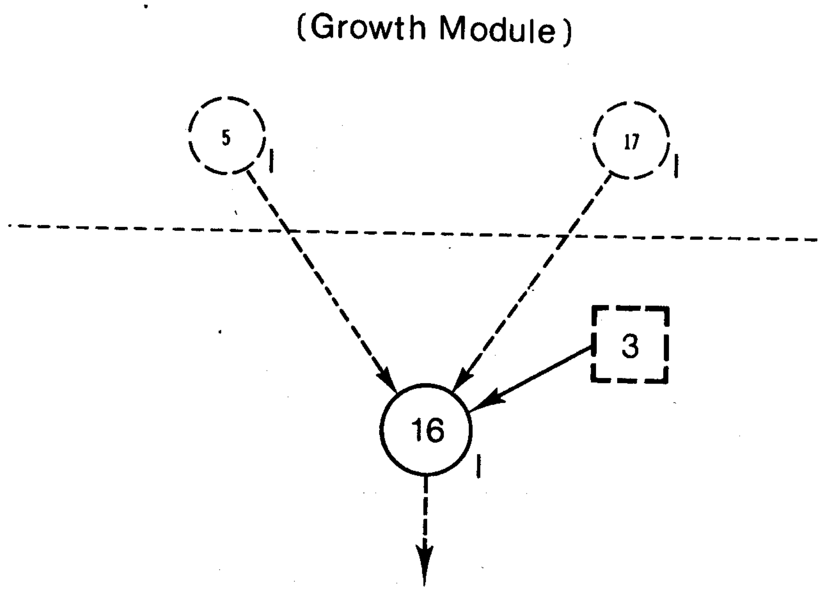
$$G_{29}(I) = \begin{cases} G_6(I) & ;\ X_2(I) > 137 \text{ cm} \\ 0 & ;\ \text{Otherwise} \end{cases}$$

$G_6(I)$ = Basal diameter growth of tree in Cohort I (cm)

$X_2(I)$ = Total height of tree in Cohort I (cm)

E.4 THE LITTERFALL MODULE

Conifer litterfall is assumed to be affected by light, to a point. When the tree is under full sun, litterfall is small; a suppressed tree sheds a proportionally larger part of its leaves. The maximum proportion of litter is species-specific, represented by a parameter. In Douglas fir, for example, the tree can lose up to 23% of its leaf biomass or an amount equal to new leaf production, whichever is greater. This means that a suppressed Douglas fir can retain about four years needles. Other species vary. Clearly, mineral nutrition is a factor, but this and other changes are planned for the future. Additional work on the mechanism of litterfall is indicated.



LITTERFALL MODULE

$G_{16}(I)$ = Litterfall from tree in Cohort I (kg)

$$G_{16}(I) = \text{Min}\left[G_{17}(I),\ T_1[X_3(I) + G_{17}(I)]\right]$$
$$T_1 = B_{30}(J)\ [1 - G_5(I)].$$

T_1 = Effect of light on litterfall (dimensionless)

X_3 = Leaf biomass of tree in Cohort I (kg)

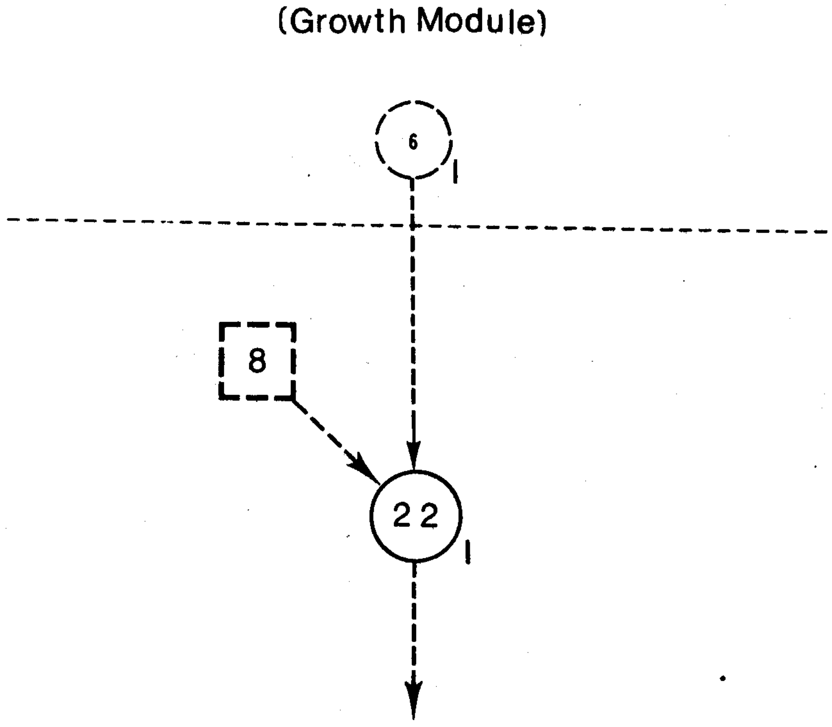
$G_5(I)$ = Effect of light on growth of trees in Cohort I, species J (dimensionless)

$G_{17}(I)$ = New leaf production in current year (kg) of tree in Cohort I

$B_{30}(J)$ = Maximum fraction of leaf biomass that can be lost as litter, species J (dimensionless)

E.5 SLOW GROWTH MORTALITY MODULE

This module assumes that mortality increases as diameter growth drops below a species-specific critical level. The critical levels are based on observations by Reed and Alan Doerksen (Oregon State University) (unpublished) on diameter growth of suppressed Douglas fir. They noticed that suppressed trees near death could put on only 2-3 cells of xylem per year. Assuming that critical slow growth is somewhat greater, we set the cut-off point for slow growth mortality at 0.05 cm for Douglas fir and raised or lowered these values by guesstimate for other species. Some work on this phenomenon is indicated.



SLOW-GROWTH
MORTALITY MODULE

$G_{22}(I)$ = Fraction of trees in Cohort I killed by slow growth

---

$$G_{22}(I) = \begin{cases} 0 & ;\ G_6(I) \geq B_{19}(J) \\ T_1 & ;\ G_6(I) \geq B_{19}(J) \text{ and } X_8(I) > 10 \\ (T_2 + T_3) \ / \ X_8(I) & ;\ \text{Otherwise} \end{cases}$$

$$T_1 = \exp\ [-B_{18}(J)\ G_6(I)]$$

$$T_2 = T_1\ X_8(I)\ [B_{34}(J) + B_{39}(J)\ X_8(I)]$$

$$T_3 = \begin{cases} 1.0 & ;\ R_n < \text{ABS}\ [T_2 - \text{INT}(T_2)] \\ 0 & ;\ \text{Otherwise} \end{cases}$$

T_1 = Relation giving fraction of Cohort I killed by slow growth when $X_8(I) > 10$

T_2 = Population-dependent mortality function when $X_8(I) < 10$

T_3 = Additional random mortality factor

$X_8(I)$ = Population of Cohort I

$G_6(I)$ = Basal diameter growth (cm y^{-1})

$B_{18}(J)$ = Exponent relating probability of mortality to diameter growth, species J (cm^{-1})

$B_{19}(J)$ = Cut-off point for slow growth mortality, species J (cm)

$B_{34}(J)$ = Threshold probability for population-dependent slow growth mortality

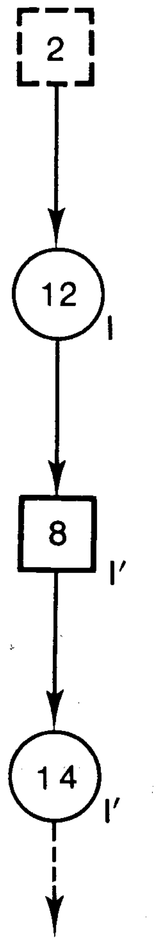
$B_{39}(J)$ = Slope of probability of population-dependent mortality to population when $X_8 < 10$

R_n = uniform random variate, $R_n \in (0.1)$

E.6 THE BROWSE MODULE

This module is based on the assumptions that animal browse can be sporadic as Reed has observed in the Glenwood, Washington area, or mostly continuous as Michael Newton and others have observed in the Oregon Coast Range (personal communication). Further, we assume that unless the seedling is clipped off or pulled up, the seedling is not killed outright, but is damaged by foliage and bud removal (Reed, unpublished data). This foliage removal causes a reduction in growth and vigor which can in itself kill the tree, or render it more vulnerable to future browse.

Our model allows browse damage to be proportional to height. The model computes a fraction of a cohort to be browsed, then decides how much leaf biomass to remove, depending on the size of the trees in the cohort. The browsed trees are removed from the original cohort and placed in a new cohort. This step can cause cohort proliferation if BROWSE is left on continually. It is preferable, and probably more realistic for the user to program browse at intervals using program interupts or an input file.



BROWSE MODULE

$G_{12}(I)$ = Fraction of trees in Cohort I to be browsed. (Note that these trees are removed from Cohort I; a new cohort is established for them.

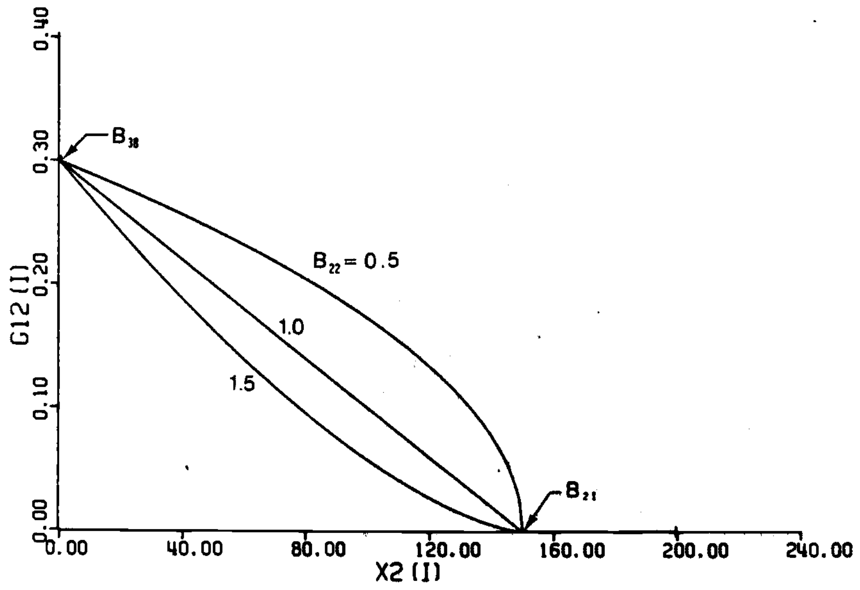
$$G_{12}(I) = \begin{cases} B_{20}(J)\ [B_{21}(J) - X_2(I)]^{B_{22}(J)} & ;\ X_2 \leq B_{21}(J) \\ 0 & ;\ \text{Otherwise} \end{cases}$$

$X_2(I)$ = Height of tree in Cohort I (cm)

$B_{20}(J)$ = Browse probability coefficient ($cm^{-B_{22}}$) (computed)

$B_{21}(J)$ = Maximum height for significant browse (cm)

$B_{22}(J)$ = Exponent relating browse probability to height (dimensionless)



$B_{38}(J)$ = Maximum fraction of Cohort I to be browsed

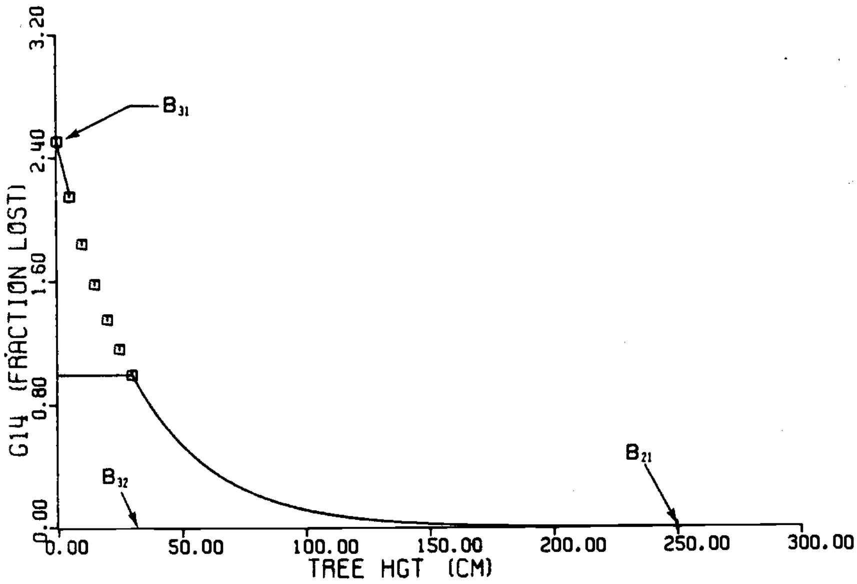
$G_{14}(II)$ = Fraction of leaf biomass lost from a tree in Cohort I due to browsing ($G_{14}(II)$ is computed only for the trees selected by $G_{13}(I)$ from old Cohort I)

$$G_{14}(II) = \text{Min}\ \{1,\ B_{31}(J) \exp\ [-B_{16}(J)\ X_2(II)]\}$$

$X_2(II)$ = Height of trees in new Cohort II (cm)

$B_{16}(J)$ = Leaf biomass browse fraction exponent, species J (computed) (cm^{-1})

$B_{31}(J)$ = Value of $G_{14}(II)$ when $X_2(II) = 0$, such that $G_{14}(II) = 1$ when $X_2(II) = B_{32}(J)$ (computed) (dimensionless)

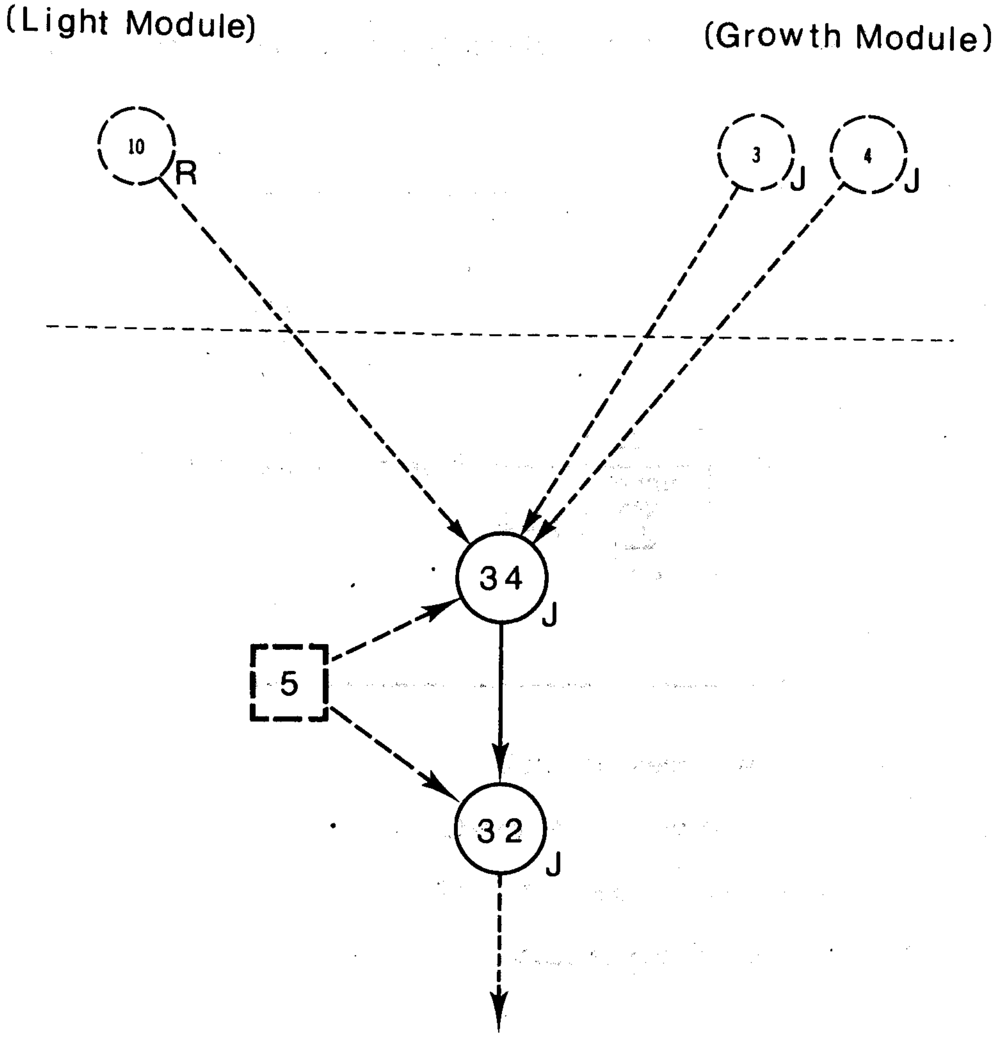


$B_{32}(J)$ = Maximum height for full defoliation due to browse (cm), species J

$B_{21}(J)$ = Maximum height for significant browse

E.7 THE ESTABLISHMENT MODULE

The establishment module is also oversimplified. It is based on the assumption that the number of seedlings introduced depends on the environmental conditions of the site: the more optimal the site, the greater the number of seedlings introduced. If several candidate species are eligible for introduction, the available "slots" for seedlings is partitioned accordingly. At present, we set a limit of 2500 trees per hectare. If there are currently 500 trees on the site, then up to 2000 seedlings could be introduced. Species whose range lies outside the environment of the cell are not planted. If, say, the environment is suboptimal, some number fewer than 2000 seedlings would be planted (see Reed and Clark 1978 for an example). The bulk of the seeding comes in seedyears—some offyear seeding is allowed. The establishment module is deterministic. Studies to improve the establishment module are in progress.



ESTABLISHMENT MODULE

$G_{34}(J)$ = Number of seedlings of species J introduced into Cohort II (new cohort)

$$G_{34}(J) = \begin{cases} G_{32}(J) & ; \sum_{J=1}^{nspec} G_{32}(J) \leq B_{36} - X_5 \\ INT\left[\dfrac{G_{32}(J)}{\sum_{J=1}^{nspec} G_{32}(J)} (B_{36} - X_5)\right] & ; \text{Otherwise} \end{cases}$$

X_5 = Number of live trees in cell

$G_{32}(J)$ = Seedling potential of species J

B_{36} = Maximum number of trees in cell

INT = Integer part of the result

$G_{32}(J)$ = Seedling potential of species J in cell

$$G_{32}(J) = G_3(J)\ G_4(J)\ T_1\ T_2\ T_3$$

$$T_1 = B_{36} - X_5$$

$$T_2 = \beta[B_{10}(J),\ B_{41}(J),\ B_{42}(J),\ G_{10}(R{=}1)]$$

$$T_3 = \begin{cases} 1 \text{ if MOD } [t,\ B_{37}(J)] = 1 \text{ and } t \neq 1 \\ B_{40} \text{ otherwise} \end{cases}$$

T_1 = Maximum number of seedlings that can be planted

T_2 = Constraint of light on maximum number of seedlings (dimensionless)

T_3 = Seedyear switch (dimensionless)

$G_3(J)$ = Effect of temperature on growth of species J (dimensionless)

$G_4(J)$ = Effect of moisture on growth of species J (dimensionless)

$G_{10}(R{=}1)$ = Light at forest floor (fraction full sun)

$B_{10}(J)$ = Minimum light for von Bertalanffy growth function, species J (fraction full sun)

B_{36} = Maximum number of trees in cell

B_{37} = Seedyear interval (years)

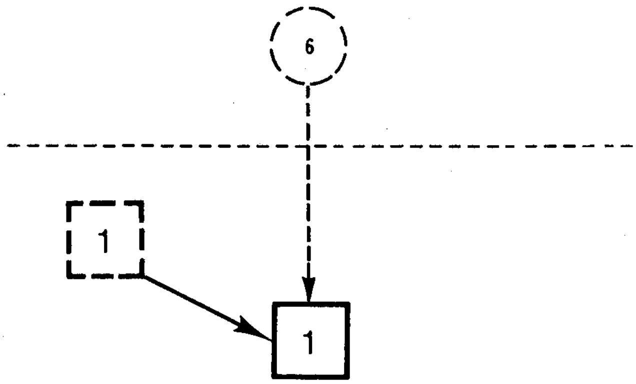
B_{40} = Offyear seedling potential

$B_{41}(J)$ = Optimum light for establishment of species J (fraction full sun)

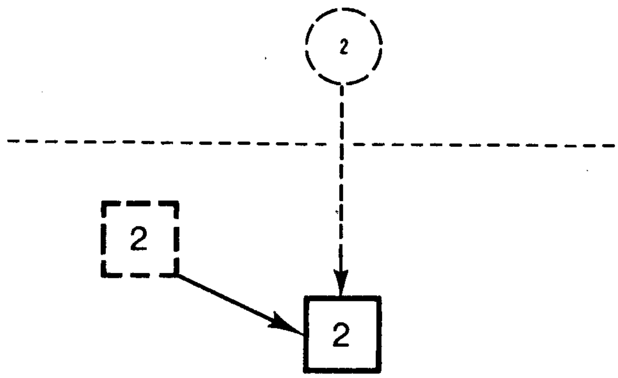
$B_{42}(J)$ = Maximum light level for establishment of species J (fraction full sun)

E.8 STATE VARIABLE UPDATES

The final step in each iteration is to update the state variables. The program then jumps to the output and monitor routines if appropriate and/or updates the RUN counters.



BASAL DIAMETER UPDATE



HEIGHT UPDATE

$X_1(I)$ = Basal diameter, Tree I (cm)

$$X_1(I) = X_1(I)' + G_6(I)$$

$X_1(I)'$ = Value of $X_1(I)$ after previous iteration (cm)

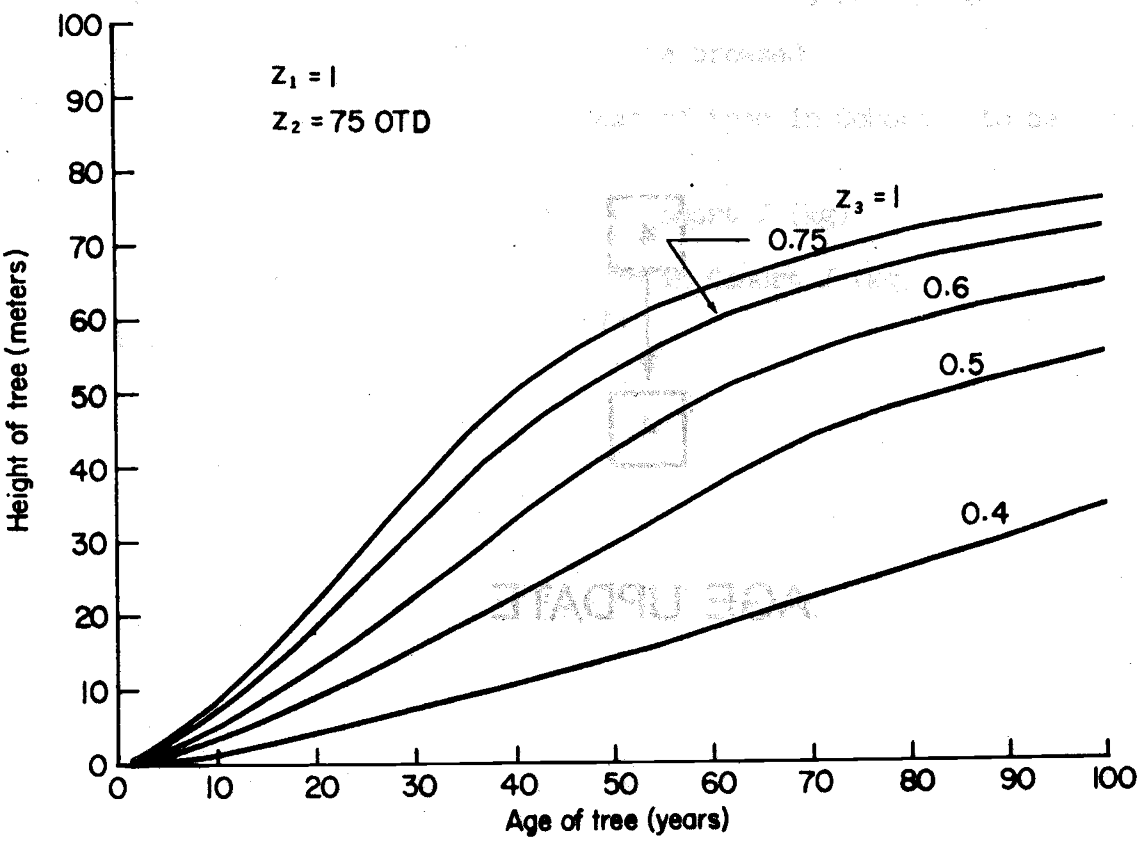
$G_6(I)$ = Basal diameter growth, tree in Cohort I

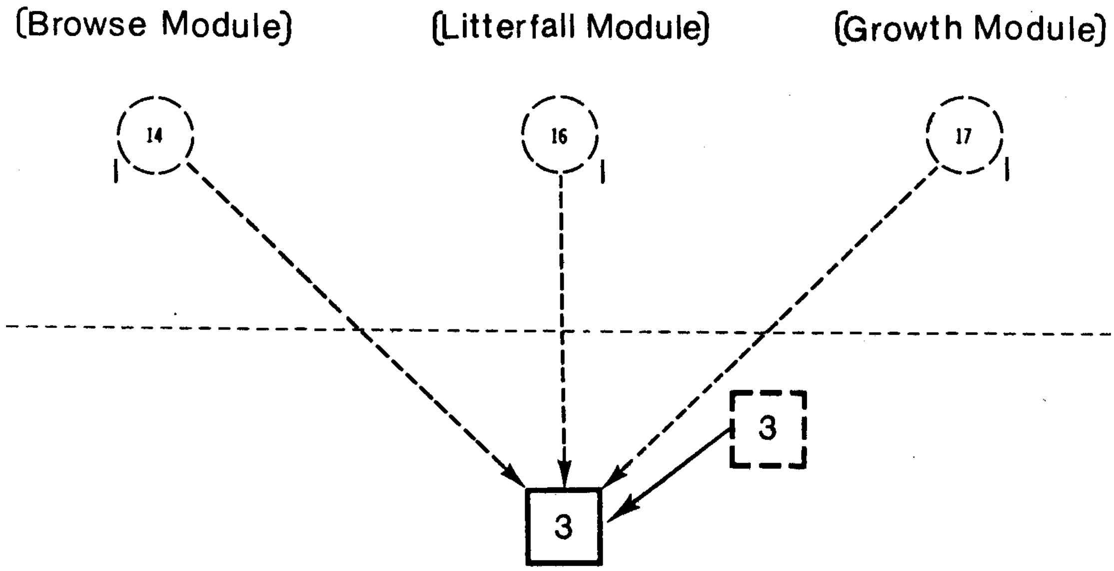
$X_2(I)$ = Height of Tree I (cm)

$$X_2(I) = X_2(I)' + G_2(I)$$

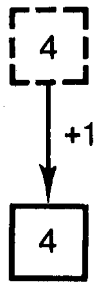
$X_2(I)'$ = Value of $X_1(I)$ after previous iteration (cm)

$G_2(I)$ = Height growth, tree in Cohort I





LEAF BIOMASS UPDATE



AGE UPDATE

$X_3(I)$ = Leaf biomass of a tree in Cohort I (kg)

$X_3(II)$ = Leaf biomass of a tree in a new Cohort II created by browsing Cohort I (kg) (all other attributes at time of creation of new cohort are equal to those of Cohort I, except $X_8(II)$)

$$G_3(I) = X_3(I)' + G_{17}(I) - G_{16}(I)$$

$$G_3(II) = X_3(I)' \, [1 - G_{14}(I)] \; ; \text{ iff } G_{14}(I) > 0 \text{ and } G_{12}(I) > 0$$

$X_3(I)'$ = Leaf biomass of a tree in Cohort I, preceding iteration (kg)

$G_{12}(I)$ = Fraction of Cohort I to be browsed

$G_{14}(I)$ = Fraction of leaf biomass of tree in Cohort I to be removed by browse

$G_{16}(I)$ = Litterfall from tree in Cohort I (kg)

$G_{17}(I)$ = New leaf biomass of tree in Cohort I (kg)

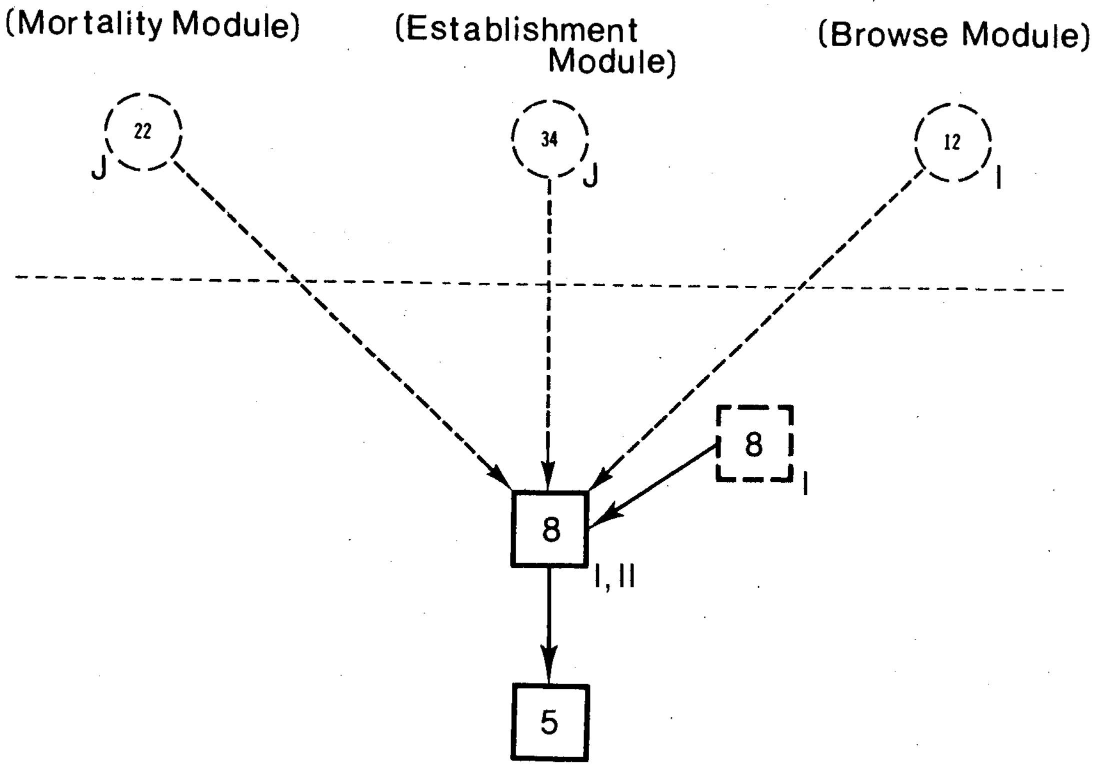
iff = If and only if

$X_4(I)$ = Age of trees in Cohort I (years)

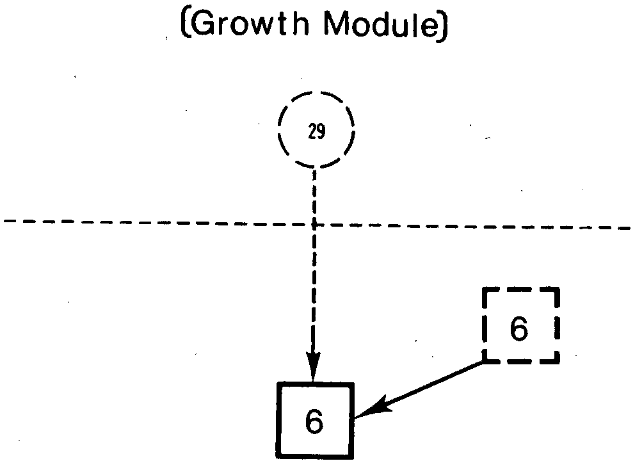
$$X_4(I) = X_4(I)' + DT$$

$X_4(I)'$ = Age of trees in preceeding iteration

DT = Run time increment (set to one year)



POPULATION UPDATE



DBH UPDATE

X_5 = Total population of cell

$$X_5 = \sum_{I=1}^{ncoho} X_8(I)$$

$X_8(I)$ = Population of Cohort I, current year

ncoho = number of cohorts in cell

Note:
X_5 is updated after $X_8(I)$

$X_8(I)$ = Population of Cohort I

$X_8(II)$ = Population of new Cohort II created when some of the trees in Cohort I are browsed

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$$X_8(I) = X_8(I)' - \text{INT}\,[G_{22}(I)\; X_8(I)'] - T_1 - T_2$$

$$X_8(II) = X_8(I) - T_1$$

$$T_1 = \text{INT}\,[G_{12}(I)\; X_8(I)]$$

$$T_2 = \begin{cases} \sum_{I=1}^{m} N(I)\,; & T_3 = I \\ 0 & ;\ \text{Otherwise} \end{cases}$$

$$T_3 = \begin{cases} 1 + \text{INT}\,(R_n\; ncoho) & ;\ T_4 > 1 \\ 0 & ;\ T_4 = 0 \end{cases}$$

$$T_4 = \text{INT}\,[(R_n\; B_{13}\; B_{44}\; /\; 10^8) + 0.5]$$

$$N(I) = \begin{cases} 1\ ;\ T_2 = I \\ 0\ ;\ \text{Otherwise} \end{cases}$$

T_1 = Number of trees in Cohort I browsed

T_2 = Number of trees in Cohort I selected to be killed by random factors; T_2 is equal to the number of times $T_3 = I$

T_3 = Random selection of cohort from which to kill a tree by random factors; T_3 is computed once for each tree to be killed.

T_4 = Number of trees on cell to be killed by random factors

$N(I)$ = Tag for counting the number of random kills in a given cohort

$X_8(I)'$ = Previous year's population of Cohort I

$G_{12}(I)$ = Fraction of trees in Cohort I browsed

$G_{22}(I)$ = Fraction of trees in Cohort I killed by slow growth

B_{13} = Total area of cell (cm^2)

B_{44} = Maximum number of trees in cell to be killed by random factors (trees ha^{-1})

R_n = Uniform pseudorandom variate, $R_n \in (0, 1)$

$ncoho$ = Total number of cohorts in cell

$X_6(I)$ = Diameter at breast height of tree in Cohort I (cm)

$$X_6(I) = X_6(I)' + G_{29}(I)$$

$X_6(I)'$ = DBH of tree in Cohort I from previous iteration (cm)

$G_{29}(I)$ = Diameter growth of tree in Cohort I at breast height (137 cm) (cm)

$X_9(I)$ = Mass of bole of a tree in Cohort I (kg)

$$X_9(I) = \frac{\pi}{12} B_{45}(J)\ X_1(I)\ X_2(I)$$

$X_1(I)$ = Basal diameter of a tree in Cohort I (cm)

$X_2(I)$ = Height of tree in Cohort I (cm)

$B_{45}(J)$ = Density of wood of species J

$X_{10}(J)$ = Total amount of dead leaf biomass of species J (kg)

$X_{11}(J)$ = Total amount of dead wood of species J (kg)

Note: These quantities could be used in future as inputs to a decomposition model. At present, they are not used by SUCSIM. These quantities are updated in SUBROUTINE KILL, NOT UPSTATE.

$$X_{10}(J) = X_{10}(J)' + X_3(I)\ T_1$$

$$X_{11}(J) = X_{11}(J)' + X_9(I)\ T_1$$

$$T_1 = \text{Min}\ [X_8(I),\ FN + 0.5]$$

T_1 = Number of trees killed in Cohort I, this pass through SUBROUTINE KILL

$X_3(I)$ = Leaf biomass of tree in Cohort I (kg)

$X_8(I)$ = Population of Cohort I

$X_9(I)$ = Bole biomass of tree in Cohort I (kg)

$X_{10}(J)'$ = Amount of dead leaf biomass from previous iteration

$X_{11}(J)'$ = Total amount of dead wood biomass from previous iteration

FN = Number of trees to be killed this pass (T_1 prevents negative values being returned)

SECTION F

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