NUTREM 2.0: A Model for Soil Nutrient Uptake and Harvest Removals in Loblolly Pine-User's Manual

NCSFNC Research Note No. 17

North Carolina Forest Nutrition Cooperative

(NCSFNC)

Department of Forestry

North Carolina State University

Raleigh

June, 2000

Foreword

This note describes the use and construction of *NUTREM 2.0*, for predicting nutrient uptake during the growth of loblolly plantations, and nutrient removals during harvest, using inventory data or growth and yield simulators as inputs. Mark Ducey coordinated *NUTREM 1.0* model construction and performed the programming and mathematical analyses presented in NCSFNC Research Note 14). *NUTREM 2.0* was constructed using previously published relationships, as well as new relationships derived from the Regionwide 13 studies and from SETRES. *NUTREM 2.0* was developed by Mark Ducey, Cristian Montes, Qingchao Li , and Lee Allen.

Requests for additional copies of this note should be addressed to the Director of NCSFNC.

Summary

A model (*NUTREM 2.0*) for soil nutrient uptake and subsequent harvest removals of established loblolly pine plantations is presented. The user supplies projections of trees per acre, basal area, dominant height, and total stemwood volume to the model. These variables can be from the growth and yield models, or from inventory data. The model returns projections of N, P, K, Ca, and Mg use throughout the life of the plantation. Where thinnings have occurred, and at the end of the rotation, the model estimates aboveground removals by compartment (stems, branches, and foliage) for all five nutrients.

Using the TAUYIELD model as the source for the scenarios, *NUTREM 2.0* projects peak nutrient utilization rates ranging from 86 lbs N/acre/yr for a site index of 70. Unusual projections of uptake sometimes observed after thinnings are related to the behavior of the growth and yield model. Specifically, the reduction in gross increment implied by the TAUYIELD model is less than the reduction of stocking. The rapid redevelopment of stand foliar biomass implied by the scenarios requires high nutrient uptake immediately following thinning.

At this time, the TAUYIELD model does not allow projections for stands less than eight years old. Also, *NUTREM 2.0*'s dependence on external growth and yield models (or, alternatively, on interpolated inventory data) for stand conditions prevents using it in "forward mode" to project the influence of changes in nutrition on growth. However, soil nutrient uptake can be projected with real inventory data starting at year 1. A model may be used to generate the growth data starting at year 1. These aspects are being addressed in a more complex model which is currently under development.

Table of Contents

Introduction

The model presented in this report is designed to answer two questions. First, what are the nutrient removals associated with harvest across a range of stand structure and growth rate? Second, and more importantly, what rate of soil nutrient uptake is required to sustain a given growth rate in loblolly pine plantations?

The quantity of nutrients removed from a site during harvest has often been considered critical to assessing the sustainability of silvicultural operations (Patric and Smith 1975, Francis and Baker 1982, van Lear *et al.* 1983, Lockaby and Adams 1986, Mann *et al.* 1988). It has been asserted that removals and leaching losses must be balanced by weathering, atmospheric inputs, and nutrient additions if the nutrient capital of the site is not to be depleted (Johnson *et al*. 1995). While much has been published concerning the role of nutrient removals in loblolly pine plantations (*e.g.* Switzer *et al.* 1973, 1978; Wells and Jorgensen 1975, 1977; Tew *et al.* 1986), previous empirical estimates of removals come from only a few studies. Our model represents a synthesis of these studies with a modern understanding of stand biology to estimate removals across a range of stand age and site conditions.

Despite the amount of attention paid to issues of nutrient removal, in general, removals may be dwarfed by the magnitude of the inputs required to achieve and maintain optimal stand growth. Furthermore, the relationship between required nutrient uptake and stand growth rate has strong implications for the development of fertilization and other soil amendment regimes. Most modeling efforts designed to address issues of nutrient use or nutrient removals have focused on the use of detailed process models to describe the dynamics of nutrients in the forest system (*e.g.,* Johnson *et al.* 1995). However, detailed process models usually require far more information than is available except on intensively studied sites, and thus provide little guidance for specific silvicultural decisions. Furthermore, such models are often computationally demanding and can require "hand-holding" by someone familiar with the details of model parameterization. Clearly, for operational assessments of stand nutrient use and harvest removals, a simpler tool is needed, but one which remains biologically reasonable across a range of site, climate, and management scenarios.

NUTREM 2.0 is a model for the soil nutrient use of loblolly pine plantations which also provides estimates of removals during thinning and final harvest. The model relies on simplified representations of many processes, with many of the simplifications gained from the accumulated experience with the Regionwide 13 installations, the SETRES study, and intensive modeling using the process model BIOMASS (NCSFNC 1996).

Model overview

NUTREM 2.0 was designed to estimate uptake of soil nutrients and harvest removals for stands using stand growth estimates derived from growth and yield models and inventory data from actual stands. It relies on information which most growth and yield models produce as output, or which would ordinarily be generated in a stand inventory. The growth and yield information is supplied to, rather than generated by, the model.

The model relies on quantitative relationships between leaf area and stemwood production, a functional balance between foliage and fine root biomass, and simplified representations of branch, coarse root, and taproot growth to estimate annual tissue construction requirements for the stand based on the provided stand growth information. The biomass of stem is the starting point to estimate the biomass of other components, the biomass production of coarse root, foliage production and branch production. The biomass of fine root was estimated by foliage biomass. Nutrient utilization was estimated by summing the products of nutrient concentration and biomass for each component (stem, coarse root, fine root, foliage, and branch). Soil nutrient uptakes are estimated by subtracting foliar retranslocation from the construction requirements. Nutrient removals at harvest are calculated based on estimated foliage production, stemwood volume, and branch volume (Figure 1).

NUTREM 1.0 estimated stemwood production by multiplying volume growth inputs with a single estimate of specific gravity. This simplification resulted in over estimation of stemwood biomass production at young ages. *NUTREM 2.0* is more flexible and allows for the inputs of either stem volume or stem biomass data. If stem volume data is provided, *NUTREM 2.0* estimates stem biomass by an age specific estimation of specific gravity. Using published data (Zobel et al. 1972), the specific gravity was modeled as an asymptotic function of age (Figure 2):

$Y = a * (1 - \exp(-b*X- c))$

Where

Y: specific gravity (lbs/ft^3); X: age; a, b, and c are constants; a: 29.66; b: 0.067; c:1.13

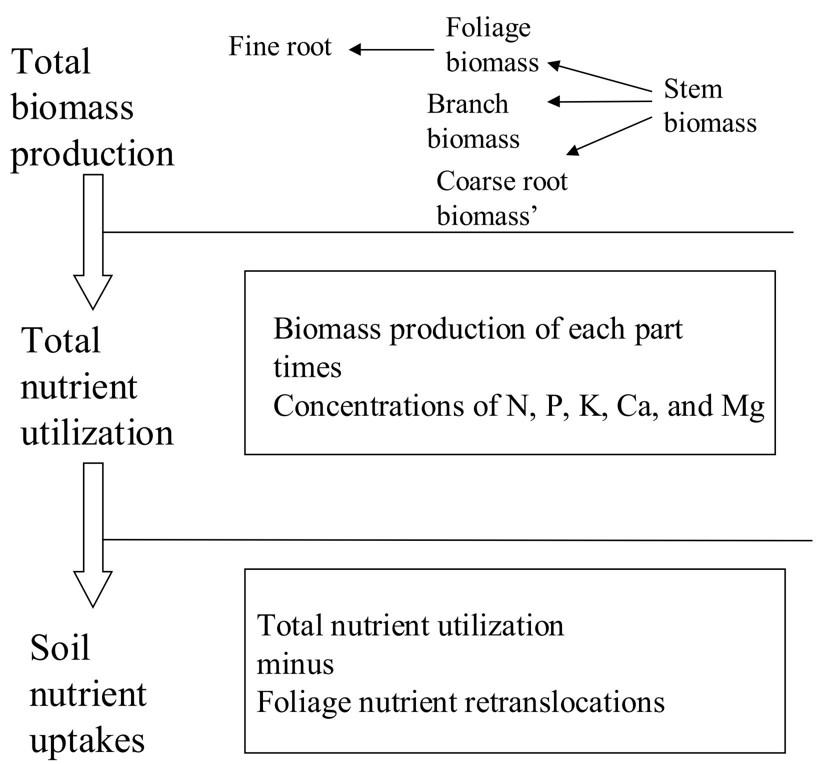

Figure 1. *NUTREM 2.0* flow chart

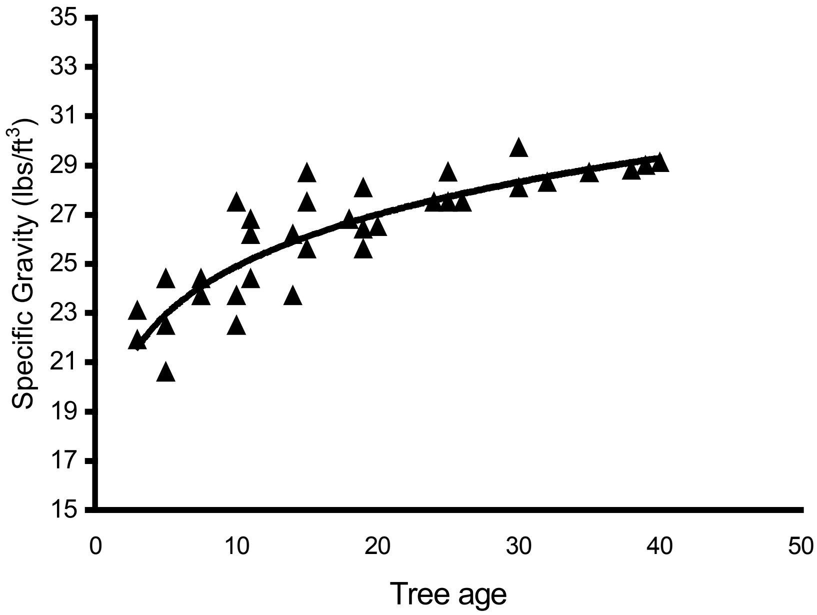

Figure 2. Relationship between specific gravity and age

One of the fundamental relationships within *NUTREM 2.0* is the relationship between leaf area and stemwood production. *NUTREM 1.0* used a fixed simple linear equation and allowed the users to specify the slope (GE) of leaf area and stemwood production relationship. *NUTREM 2.0* provided options to describe the relationship of leaf area and stemwood production recognizing the relationship is not always best described as a linear model and that climatic conditions can have considerable influences on GE. Using stemwood growth, leaf area, and climatic data from RW13 and CRIFF400 studies (NCSFNC, 1991), stemwood production was modeled as a nonlinear asymptotic function of leaf area with the form of:

VG = a * (1-exp(-b*LAI))

Where: VG is ft^3/acre/year; a and b are the constants of 579.0 and 0.2956. LAI is projected leaf area.

Further analysis revealed that this base model could be improved by incorporating growing season (April to September) rainfall (rain), average minimum temperature (^oF, mint), and average maximum temperature (^oF, maxt) to modify parameters of a and b:

$$a = 2.453322627*rain + 5.8168074714*maxt - 0.027648862*maxt^2 + 4.839837464*mint - 0.018506291*mint^2$$

$$b = 0.0025423607*rain - 0.0014853572*maxt + 0.01367478158*mint - 0.0001405263*mint^2$$

The analysis indicated that greater rainfall and lower minimum temperature increased GE (Figure 3 and 4) and greater maximum temperature decreased GE (Figure 5). The impact of increasing minimum temperature was most pronounced at lower temperatures. Given the range in temperature and rainfall that exist across the range of loblolly pine and between year at any one location, the model suggests that GE will vary 2 times. Such variation will result in large difference in nutrient utilization.

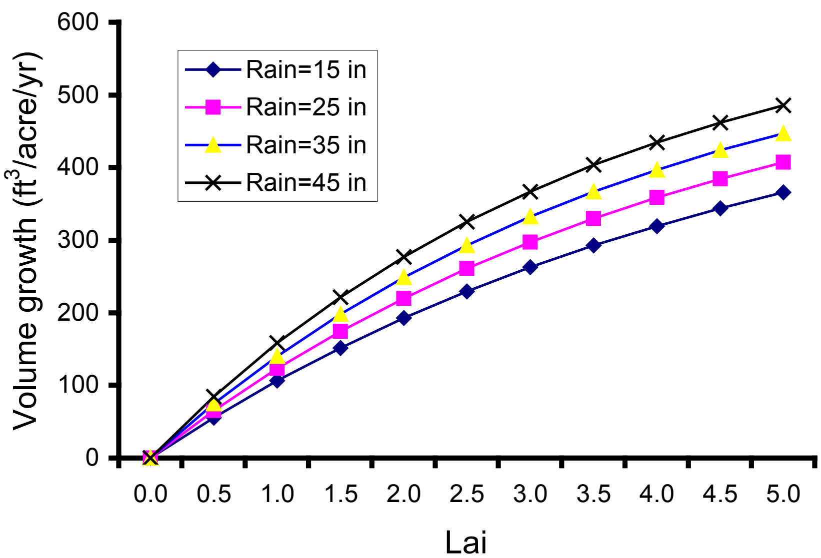

Figure 3. Rainfall effects on leaf area growth efficiency

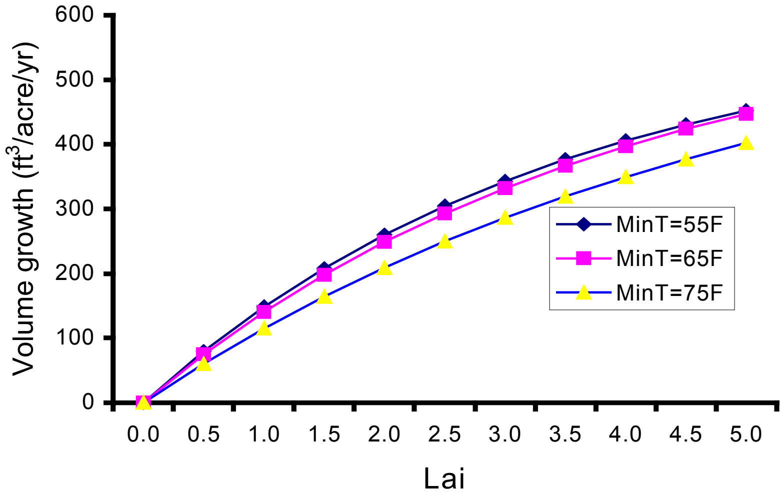

Figure 4. Average minimum temperature effects on leaf area growth efficiency

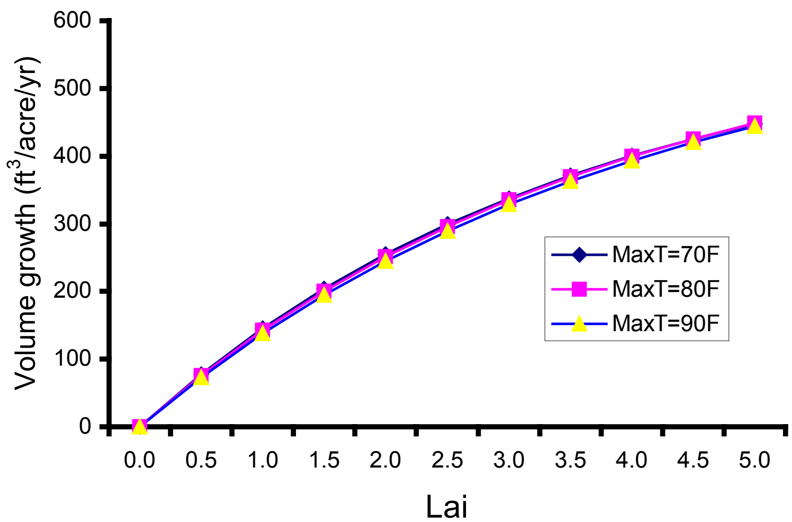

Figure 5. Average maximum temperature effects on leaf area growth efficiency

System of *NUTREM 2.0*

NUTREM 2.0 is Microsoft compatible software using the MS-ACCESS engine to develop its database. *NUTREM 2.0* software provides a user friendly interface. Also *NUTREM 2.0* allows the introduction of measurement data, importation of old *NUTREM* 1.0 data, or to creation of a new data using a Growth and Yield Model (TAUYIELD). Users can change the default control file (model parameters) to customize model simulations. Thus, every data set can be run using several different control files or several data sets can be run using one control file. *NUTREM 2.0* software includes a batch mode where users can select a list of data sets and specify the control file to use for each run. Furthermore, *NUTREM 2.0* has a dynamic link library, which allows programmers to build their own interface and to include *NUTREM 2.0* model in other software.

How to run the model

System requirements:

NUTREM 2.0 was compiled in Visual C++ and Visual Basic. A Windows 95/98/2000/NT platform and a 100 MHz Pentium with SVGA video card are required.

System installation

The *NUTREM 2.0* system can only be installed from the North Carolina State Forest Nutrition Cooperative web page, http:\\ncsfnc.cfr.ncsu.edu\nutrem\install.htm and selecting the installation link. The browser will show a dialog box asking you to either save or open the file. Opening the file will cause immediately installation of the package, saving will allow you to save the installation package to the user's hard-drive for a later installation. The installation will be done automatically. Users only need to answer *yes* to the rebooting question and follow instructions after rebooting is complete.

The Installation program will prompt you for a destination folder for the program (by default it will be installed in "\program files\NUTREM2").

NUTREM 2.0 main screen

The main program screen allows users to select whether they want to add or generate the data, set model parameters, set up batch mode, run the model, or exit (Figure 6).

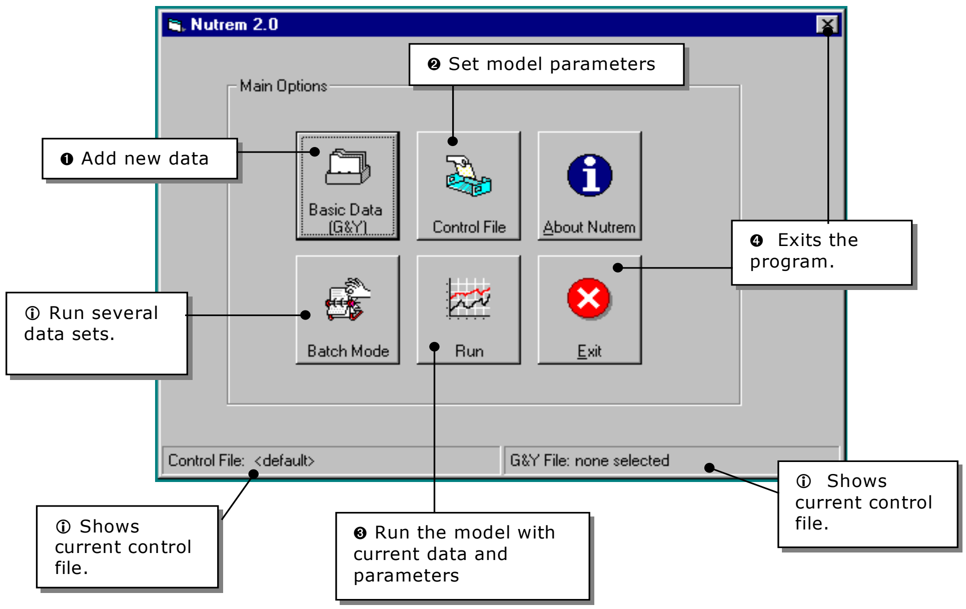

Figure 6. The main screen of *NUTREM2.0*

Preparing data for the model

Before you can run the model, you will need to create files containing the information for the stand or stands you wish to simulate. Exactly how you choose to create these files depends on the source of your data and the software with which you typically work. However, *NUTREM 2.0* requires a fixed data structure no matter what method users choose to create the data sets.

Input files for *NUTREM 2.0* must be MS-ACCESS files, and must present the required data in the proper format. Each year of data is represented by one line in the input file. Although the file can start at any age, annual data must be present for the time period to be simulated. You do not need to indicate when thinnings have occurred; the model identifies thinnings automatically.

For each year, five variables are required. The order of the data in each line must be:

AGE TPA BA H VOL(or WEIGHT)

where

AGE is stand age in years

TPA is number of living trees per acre

BA is basal area in ft^2/acre

H is mean tree height in feet

(If mean tree height is unavailable, substituting dominant height will not affect the results dramatically.)

VOL is total stemwood volume outside bark in ft^3/acre. (Substituting merchantable volume for total volume dramatically affect the results).

An example of an input file generated from a growth and yield model is shown in Table 1. Converting growth and yield model output into input for *NUTREM 2.0* is fairly straightforward for most models, using either a spreadsheet, a word processor, or a text editor to delete any unwanted header lines and to reorder the columns as necessary. Note that the results must be saved as a MS-ACCESS file; *NUTREM 2.0* can only read MS-ACCESS data files as input.

Table 1 An example input data file in MS-ACCESS form for *NUTREM 2.0*

Data

File Edit

Inputs				
AGE (year)	Trees per Acre	Basal Area (ft2/acre)	Height (ft)	Volume (ft3/acre)
1	799	.1	5.7	1.2
2	796	.2	10.0	2.2
3	791	.7	13.9	4.3
4	785	3.6	17.5	5.6
5	776	9.5	20.9	13.5
6	766	17.9	24.2	25.6
7	755	28.1	27.3	89.6
8	743	39.2	30.2	210.6
9	729	50.6	33.1	390.2
10	714	62.0	35.9	621.2
11	699	73.0	38.6	892.4
12	683	83.5	41.2	1192.5
13	666	93.3	43.8	1511.3
14	649	102.4	46.3	1840.3
15	632	110.8	48.7	2172.9
16	614	118.5	51.0	2504.0
17	597	125.5	53.3	2829.8
18	579	131.8	55.6	3147.5
19	562	137.6	57.8	3455.2
20	545	142.7	59.9	3751.4
21	528	147.3	62.0	4035.3
22	512	151.4	64.1	4306.5
23	496	155.1	66.1	4564.9
24	480	158.3	68.1	4810.4
25	465	161.2	70.0	5043.3

If estimates of nutrient use and potential removals are to be made using data from a single inventory measurement, *NUTREM 2.0* will still need two years of "data" in order to perform its calculations. The following method will provide satisfactory results:

1) Create a line containing the stand age, TPA, BA, height, and total outside bark volume as calculated from the inventory. This line will become the *second line* of the input file.

2) On the *preceding* (*first*) *line*, enter the following values:

Stand age minus one

TPA or TPA plus an estimate of annual mortality

BA less an estimate of current annual basal area increment

Stand height less current height increment

Total outside bark volume, less an estimate of current annual volume increment

An example of input data created from single inventory estimates is shown in Table 2. The stand is inventoried at age 15; the column for TPA indicates no change since age 14, indicating zero mortality. The stand has a basal area of 95 ft^2/acre, and is growing at 7 ft^2/acre/yr. Stand height is 42 ft, with an estimated current increment of 2 ft/yr; stand volume is estimated at 1500 ft^3/acre, with a CAI of 250 ft^3/acre/yr.

Table 2. Example of input file using only a single year's inventory

Data

File

Inputs				
AGE	TPA	BA	H	VOL
14	650	88	40	1250
15	650	95	42	1500

Close

Using the interface of *NUTREM 2.0* for data input

The *NUTREM 2.0* data input interface provides users with 3 choices (Figure 7). First, users can use the "New" button to create a new data set by using the growth and yield model (TAUYIELD). Also users may input a data set through a MS-ACCESS data table. Finally, users can click the "Open" button to use existing data sets.

If you select "New" from the menu, the program will ask the user for the name of the file to be created, or using TAUYIELD model to generate a data. This file will be created and saved in a user specified folder. The format of data file is MS-ACCESS file that contains one table called DATA. The opened file will look like Table 1, and includes the basic information: AGE (the age for current observation), TPA (Trees per Acre), Basal Area (ft^2/acre), Height (ft.) and Volume (ft^3/acre). The information in the Data Screen can be edited just like MS-ACCESS database.

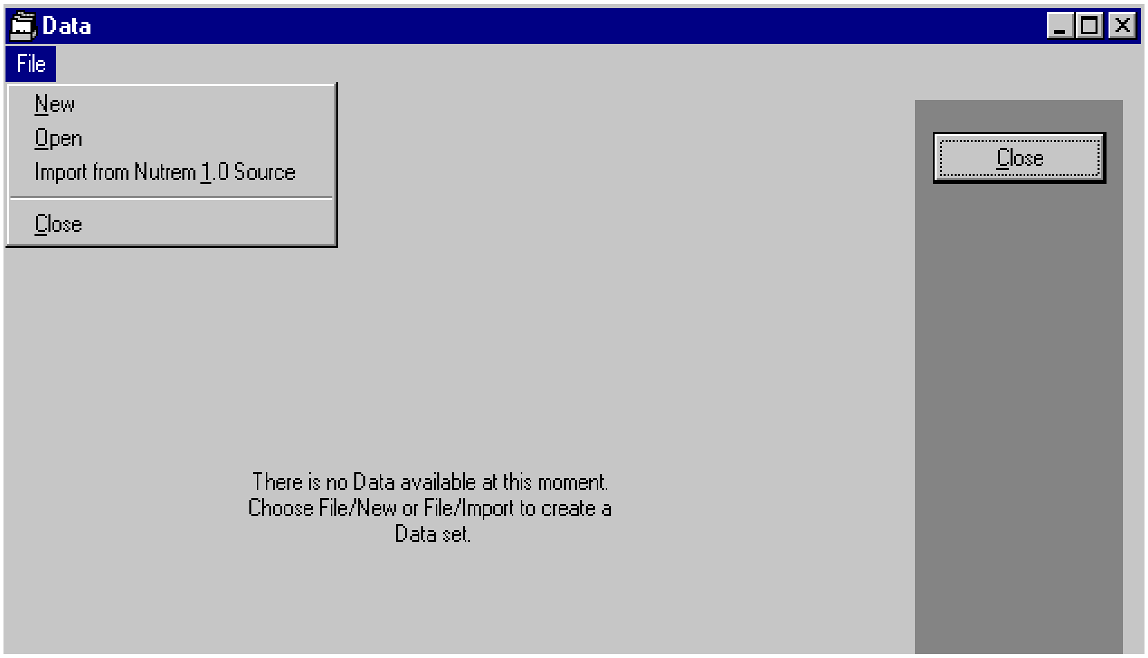

Figure 7. Data input interface screen with unopened Data

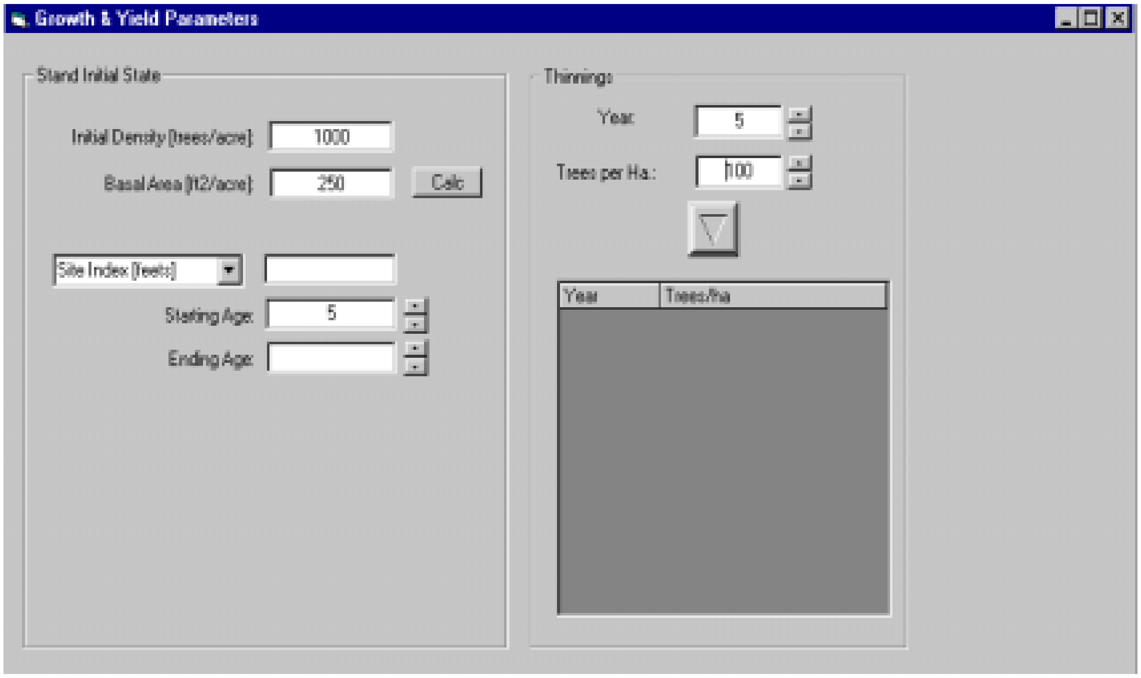

Figure 8. The interface of growth and yield model

NUTREM 2.0 incorporated TAUYIELD growth and yield model for loblolly pine plantation. However, users can use any models to generate the input data for *NUTREM 2.0*. If you select creating a new data set by TAUYIELD model, you need to input the stand growth conditions to run the model. The TAUYIELD model interface face screen is shown in Figure 8.

Modifying the control file

NUTREM 2.0 parameters can be modified to create a user customized model (Figure 9). There are six major functions for the control file, including Main, Tissue, Volume and weight relationship, Foliage biomass, Allometric equation, and Foliage and fine root relationship. The parameters for each function may be modified by clicking the proper tabs. A new control file (user customized control file) can be created by clicking the "New" button. Previously saved control files can be opened by clicking the "Open" button. We recommend user limit changes to some parameters in Table 3. Changing other parameters may lead nonsensical results.

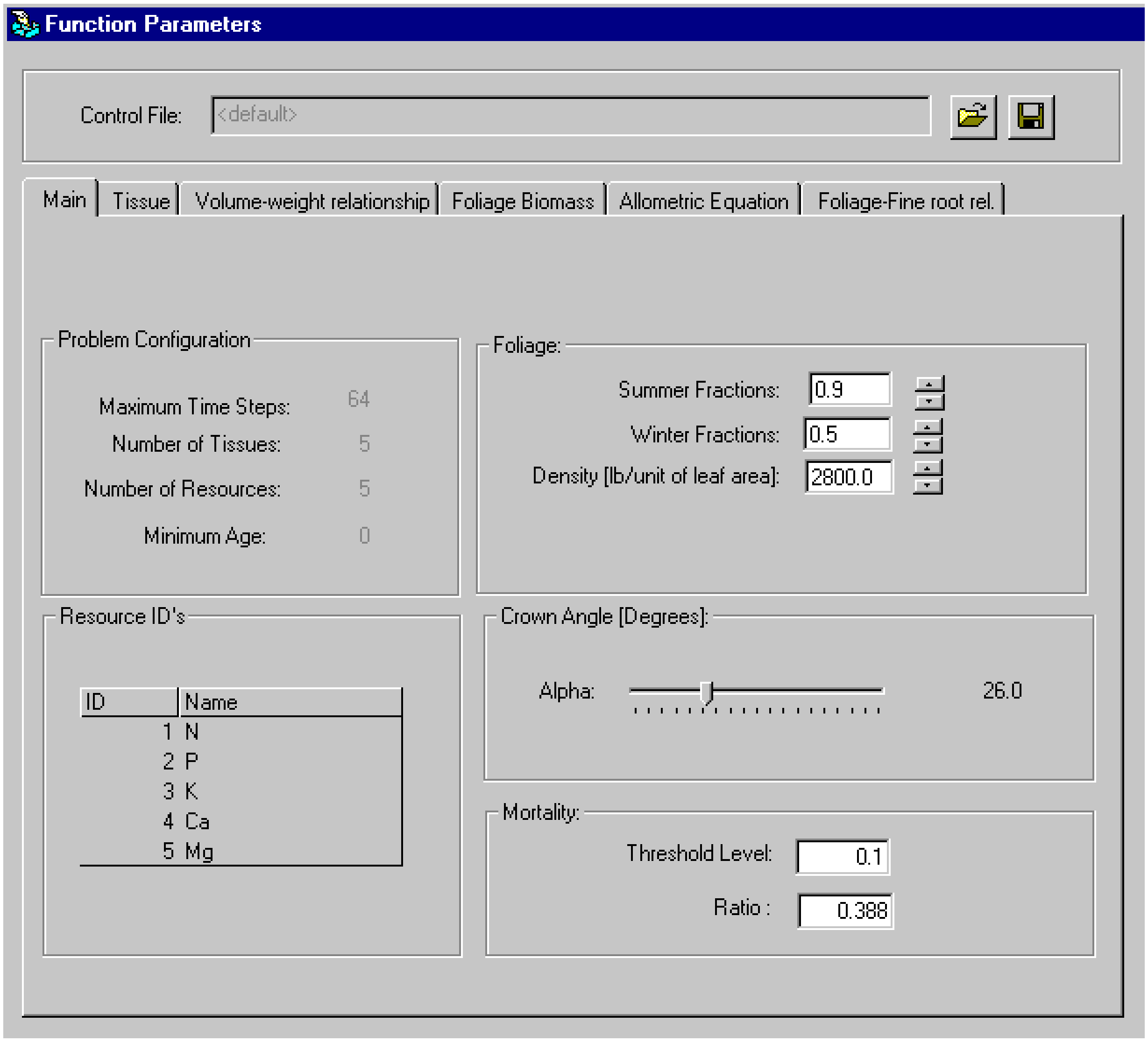

Figure 9. Control file screen

Table 3. Recommendation for modifying the parameters in the control file

Main function
Problem configuration parameters (Fixed) Number of time steps: 64, Number of tissues: 5; Number of resources: 5
Resource ID's (Fixed) N: 1; P: 2; K: 3; Ca: 4; Mg: 5
Foliage Summer fractions: 0.9; Winter fractions: 0.5; Foliage density: 2800 lbs/LAI Changeable, user can change them based on actual data or the best guess.
Crown angle (Changeable) A=26.00 User can change them based on actual data or the best guess.
Mortality Threshold level: 0.1; Ratio: 0.388 User can change the threshold level for mortality and thinning and the ratio of self-thinned tree volume verses average tree volume
Tissue
Foliage, Stem, Branch, Coarse root, and fine root (Changeable) Concentration: average concentration for N, P, K, Ca, and Mg in foliage Concentration ratio: concentration ratio between other components and foliage for N, P, K, Ca, and Mg Retranslocation: average retranslocation rate for N, P, K, Ca, and Mg in foliage User can change them to actual numbers or best guess, less recommended
Volume-weight relationship
density: 29.32 lbs/ft^3 Percent moisture: 100 Age-dependent density: Scale parameter: 29.66, Shape parameter: -0.067, Location parameter: -1.13

They are not recommended to be changed by users
Foliage biomass
Equation 1 (changeable) Linear stemwood growth efficiency: 100 ft^3/acre/lai User can change it to a actual number or a best guess
Equation 2 (changeable) Parameter A: 579 Parameter B: -0.2956 They are not recommended to be changed
Equation 3 (changeable) Growing season rainfall: 30 in Growing season mean maximum temperature: 75^{o}F Growing season mean minimum temperature: 55^{o}F Users can input the actual climatic data A and B parameter coefficients are fixed
Allometric equation
Parameters of b_o, b_1, b_2, and b_3 are fixed
Foliage-Fine root relationship
Maximum fine root biomass: fixed Foliage biomass at half maximum roots: fixed

Running the model and model output

Once data is provided, run *NUTREM 2.0*, by selecting "run" button on the main screen. Once the model ran, three kinds of outputs are available in the output's screen by clicking the appropriate tabs. 1. Under the data tab, four tables (Growth and Yield, Nutrient Uptakes (lbs/acre), Biomass Production (lbs/acre), and Nutrient Removals at harvesting time (lbs/acre) are available. 2. Under the graphic tab, graphics of all the plain output data are available. 3. Under the reports tab, can be printed directly from the screen or exported to several common file formats (Word, Excel, dBase, HTML etc.).

Table outputs

The model produces several simple output tables suitable for export. The stand yield table includes the age, trees per acre (TPA), basal area (BA), height (H), and volume (VOL) (Table 4). The yearly production table includes variables of age, stem biomass production, foliage biomass production, and fine root biomass production (Table 5). The soil nutrient uptake table includes age, N, P, K, Ca, and Mg (Table 6). The harvest removal table of nutrients includes the variables of N, P, K, Ca, and Mg for stem, branch, foliage in summer, and foliage in winter (Table 7). Every table is a plain text file that can be imported easily into most word processors, spreadsheets, and graphics programs. If you import the file into a word processor, you will want to set the font to a fixed-pitch font such as Courier so that the columns will line up correctly.

Table 4. Stand yield output table

AGE	TPA	BA	H	VOL
1	799	0.1	5.7	1.2
2	796	0.2	10	2.2
3	791.2	0.7	13.9	4.3
4	784.6	3.6	17.5	5.6
5	776.3	9.5	20.9	13.5
6	766.4	17.9	24.2	25.6
7	755.2	28.1	27.3	89.6
8	742.6	39.2	30.2	210.6
9	728.9	50.6	33.1	390.2
10	714.3	62	35.9	621.2
11	698.8	73	38.6	892.4
12	682.6	83.5	41.2	1192.5
13	666	93.3	43.8	1511.3
14	648.9	102.4	46.3	1840.3
15	631.6	110.8	48.7	2172.9
16	614.1	118.5	51	2504
17	596.6	125.5	53.3	2829.8
18	579.2	131.8	55.6	3147.5
19	561.9	137.6	57.8	3455.2
20	544.9	142.7	59.9	3751.4
21	528.1	147.3	62	4035.3
22	511.7	151.4	64.1	4306.5
23	495.8	155.1	66.1	4564.9
24	480.2	158.3	68.1	4810.4
25	465.1	161.2	70	5043.3

Table 5. Stand production table

	Age	Stem	Fineroot	Foliage
	1	0.0110067	2.969437	521806E-03
	2	0.0110067	2.969866	362781E-03
	3	356673E-02	2.95329	080744E-02
	4	599861E-02	2.96398	545101E-03
	5	167106E-02	2.869096	435809E-02
	6	0.1444246	2.80883	652174E-02
	7	0.7643085	2.222899	0.3699211
	8	1.479546	1.762543	0.6643897
	9	2.249075	1.411558	1.045232
	10	2.962767	1.167554	1.421728
	11	3.563591	1.003073	1.774267
	12	4.040301	0.8927394	2.076787
	13	4.397034	0.8205222	2.312581
	14	4.651629	0.7748678	2.479526
	15	4.81946	0.748902	2.577678
	16	4.919623	0.7370022	2.619561
	17	4.963248	0.7361987	2.611895
	18	4.962852	0.7437196	2.568612
	19	4.93165	0.7569007	2.504011
	20	4.86853	0.7760822	2.415071
	21	4.791375	0.7978036	2.325498
	22	4.695169	0.8232747	2.223748
	23	4.586151	0.8514174	2.121002
	24	4.478005	0.8794684	2.027508
	25	4.358098	0.9102961	1.927742

Table 6. Soil Nutrient uptake output table

AGE	N	P	K	Ca	Mg
1	58.60389	4.985709	12.86482	12.25412	4.593966
2	58.60913	4.98614	12.86556	12.2553	4.594298
3	58.55124	4.985831	12.91624	12.25889	4.608783
4	58.55054	4.982785	12.87168	12.25081	4.596197
5	58.21549	4.981995	13.16521	12.2966	4.689399
6	57.92974	4.975908	13.34332	12.29498	4.736656
7	58.88681	5.283346	16.55741	13.40874	5.774935
8	63.30896	5.915031	20.8929	15.33131	7.181836
9	67.51687	6.54548	24.82376	18.2294	8.880386
10	73.51383	7.310277	28.98974	21.33815	10.62952
11	78.0714	7.912033	32.14581	24.25504	12.16556
12	81.4529	8.369654	34.47545	26.7366	13.42288
13	83.32336	8.655015	35.92375	28.67092	14.36108
14	83.97794	8.79941	36.67783	30.07065	15.0093
15	83.70048	8.832357	36.8987	30.96629	15.39871
16	82.87073	8.793434	36.77715	31.45382	15.58802
17	81.67368	8.702518	36.40991	31.58829	15.60962
18	80.28874	8.579786	35.88766	31.45752	15.50784
19	78.99345	8.454163	35.33953	31.15381	15.33233
20	77.509	8.300963	34.65758	30.66314	15.0674
21	76.23692	8.161796	34.02248	30.12711	14.78708
22	74.94923	8.014723	33.34245	29.48889	14.46015
23	73.56423	7.855175	32.59247	28.80915	14.10844
24	72.5561	7.729059	31.98177	28.1666	13.784
25	71.36658	7.58322	31.27479	27.46745	13.42665

Table 7. Soil nutrient harvest removals output table

AGE	Source	N	P	K	Ca	Mg
25	Stems	154.5867	13.77227	91.2624	90.99538	52.13789
	Branches	55.7504	7.703691	32.88227	18.2634	9.770053
	Foliage(S)	77.05082	6.864528	26.75765	12.95855	7.424897
	Foliage(W)	42.80601	3.813626	14.86536	7.199193	4.124943

Chart outputs

NUTREM 2.0 provides two types of chart outputs, a line chart (Figure 10) and a pie chart (Figure 11). The line chart can be customized for users to select the X axis and Y axis variables (Figure 12). For converting the table data into charts, users select the output table data files first, then click the chart option at the bottom of data output window, then select the chart type. All of the output charts can be copied by clicking the "copy chart" tab and pasting into other documents.

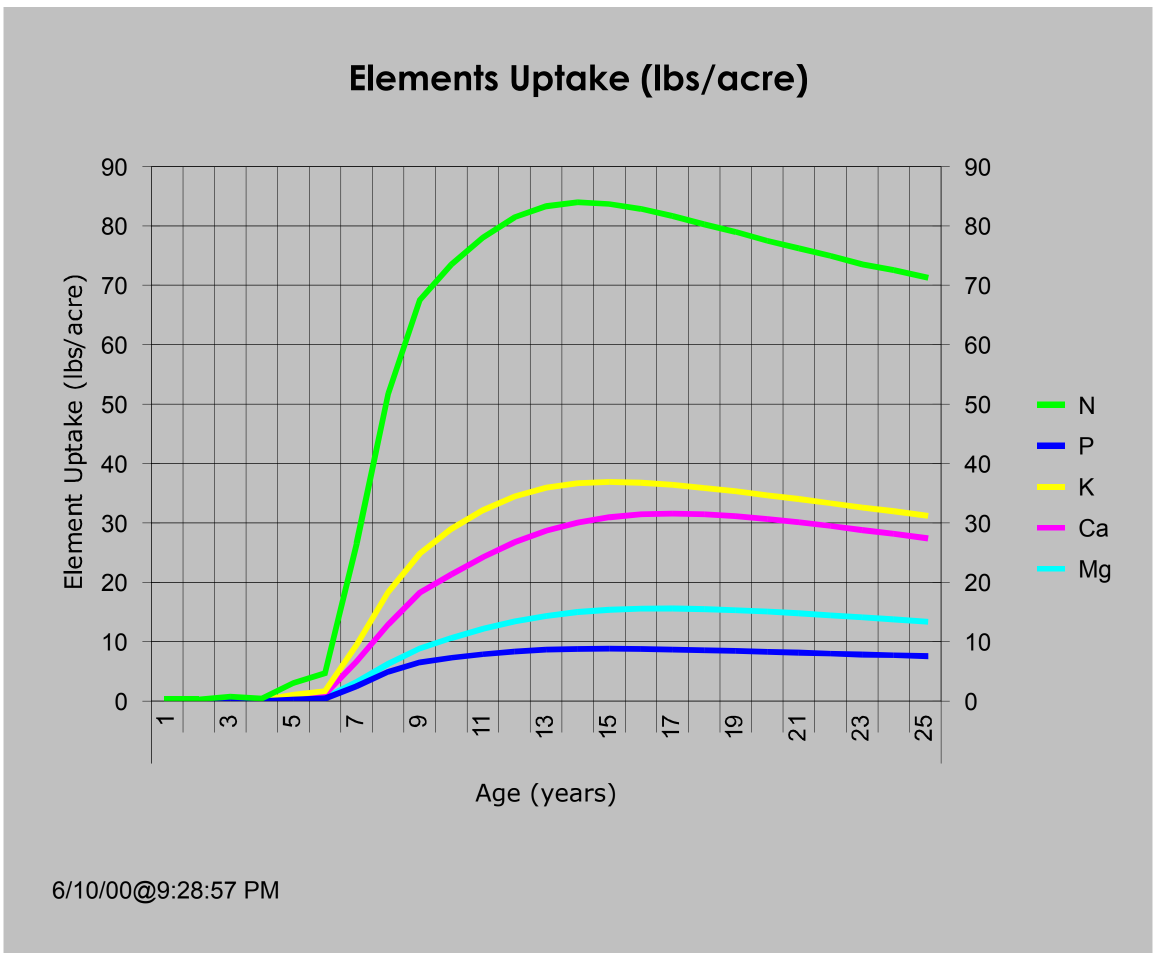

Figure 10. Soil nutrient uptake (line chart)

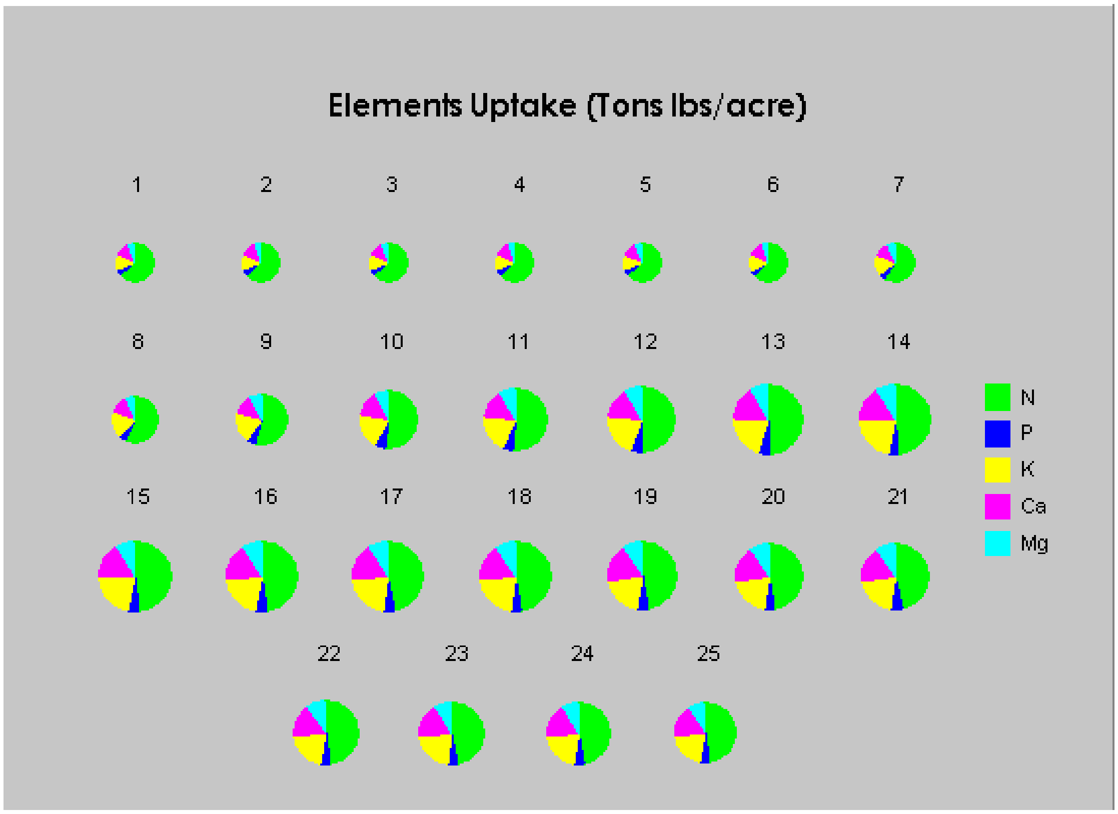

Figure 11. Soil nutrient uptake (pie chart)

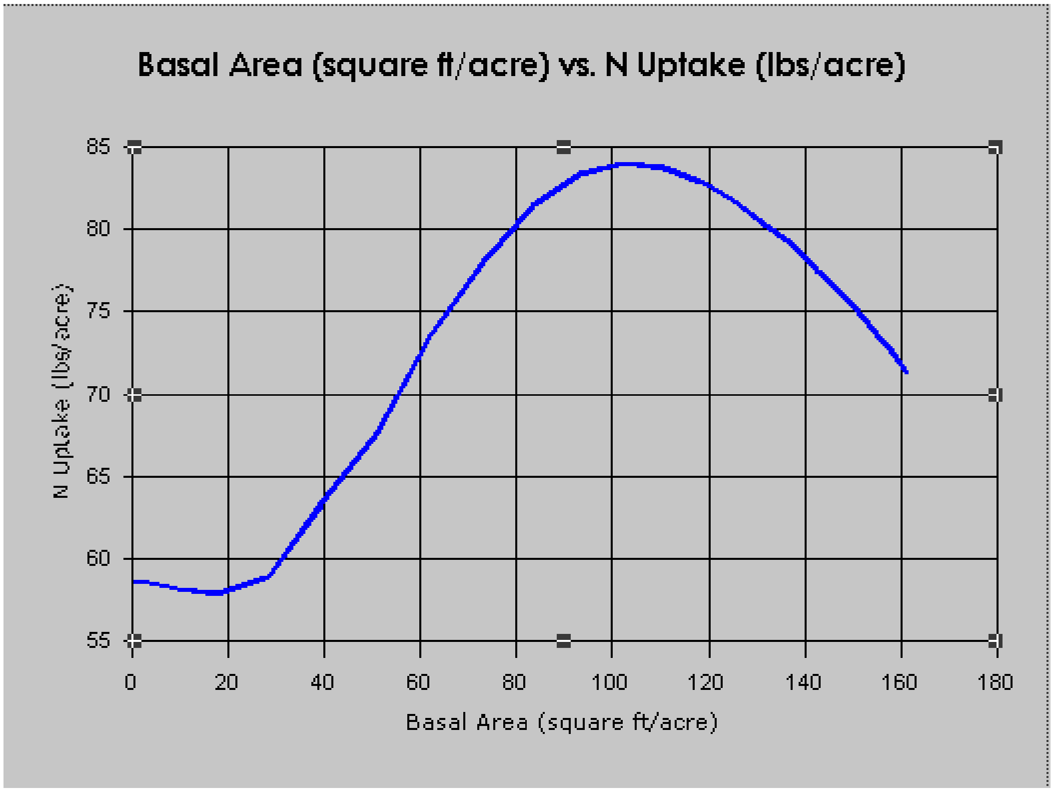

Figure 12. User's customized output figure example, Basal area vs. N uptake

Report output

NUTREM2.0 also provides data table output files and charts in report form allowing users to export the model results into other documents.

Details of the model

Mortality and gross increment

A series of steps are involved in converting observed or predicted net growth rates into gross nutrient requirements and uptake rates. The first step is to estimate gross volume increment from net volume increment and mortality. Gross and net increment (assuming ingrowth is negligible) are related by the following equation:

$$\Delta V_{gross} = \Delta V_{net} + \Delta V_{mortality}$$

Unfortunately, most inventories and most growth and yield models provide no direct estimate of the volume lost to mortality. If the average volume of trees dying due to self-thinning were negligible, we could assign $\Delta V_{mortality}$ a value of 0. For most stands, this would undoubtedly represent an underestimate. If, on the other hand, the average volume of trees dying were the same as the average volume of trees in the stand, we would assign

$$V_{mortality} = (TPA_{t-1} - TPA_t)\frac{V_{t-1}}{TPA_{t-1}} \qquad \textbf{(1)}$$

This would provide an accurate estimate if mortality were due to a silvicultural operation such as a row thinning. However, since trees dying during self-thinning are typically smaller than the average tree in a stand, this would represent an overestimate in nearly all stands. We can scale smoothly between these two extremes by introducing an empirical parameter m_1:

$$\Delta V_{mortality} = m_1\left[(TPA_{t-1} - TPA_t)\frac{V_{t-1}}{TPA_{t-1}}\right] \qquad (2)$$

Analysis of self-thinning mortality occurring between two-year remeasurements on the Regionwide 13 plots indicates $m_1 = 0.388$ (Figure 1). In the *NUTREM* model, mortality is treated as resulting from a row thinning if the mortality rate exceeds a specified threshold. If

$$\frac{(TPA_{t-1} - TPA_t)}{TPA_{t-1}} \geq m_2$$

then equation (1) is used to estimate mortality, and gross increment is estimated based on the previous two years' growth trend. Otherwise, mortality is assumed to have resulted from self-thinning, and equation (2) is used. The parameter m_2 is set by default at 0.10.

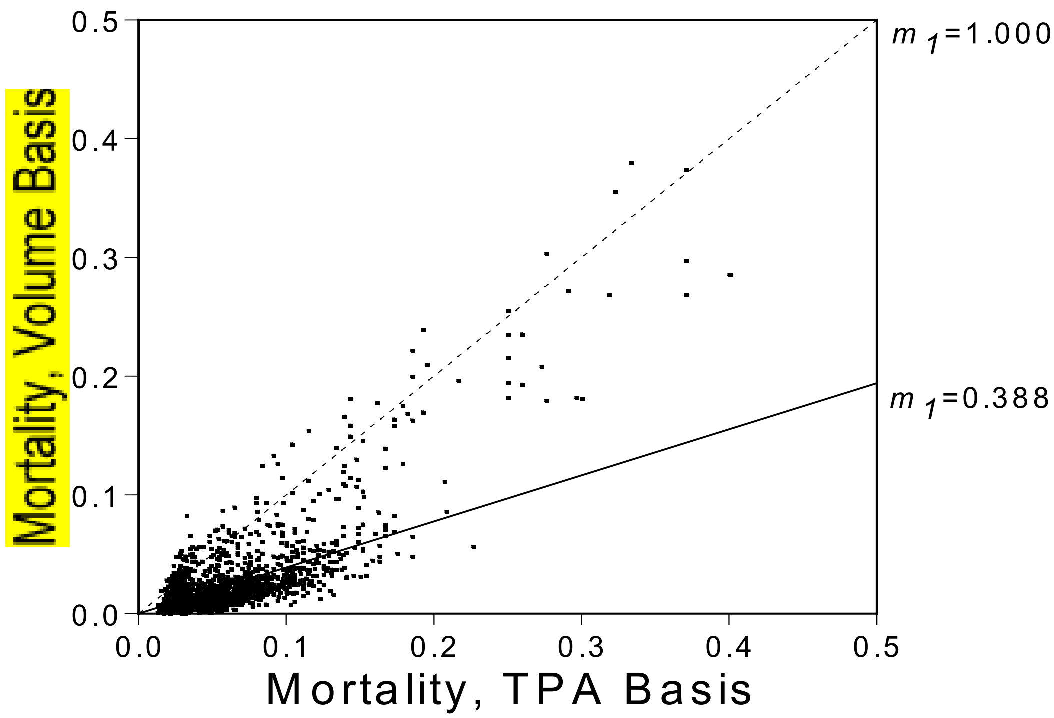

Figure 12. Two-year mortality on the RW13 plots

Two-year mortality on the RW13 plots were expressed with two values for m_1 indicated. While a few plots have m_1 near 1.000, suggesting bark beetle or other catastrophic damage, most are clustered around the average of 0.388.

Woody tissue construction

Once gross stemwood production has been calculated and converted to a dry weight basis, annual production of branch wood, coarse roots, and tap roots are calculated using tissue-specific ratios. Data on annual biomass production of woody tissues is almost nonexistent for loblolly pine stands. The default parameters for *NUTREM 2.0* are based on data from the SETRES study site (Albaugh *et al.*, 1998). The relationship between branch, coarse root, and stemwood production is depicted in Figures 13 and 14.

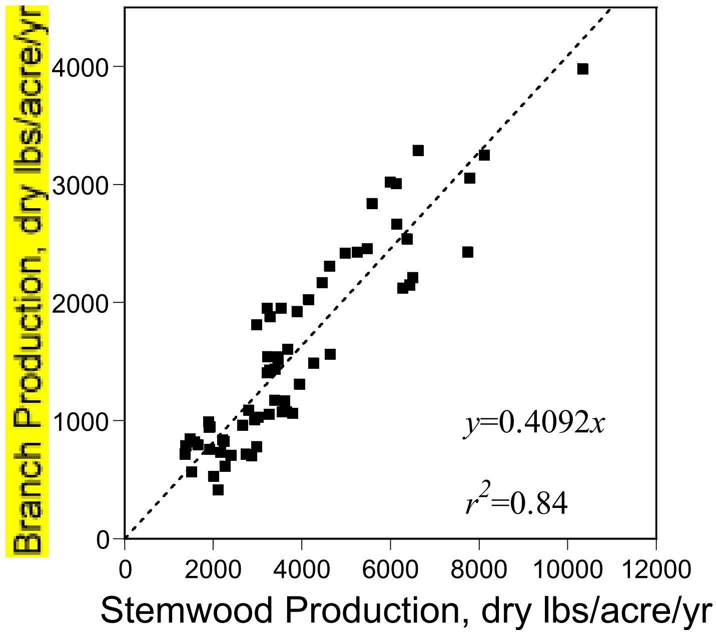

Figure 13. Relationship between branch production and stemwood production for SETRES, 1992-1995.

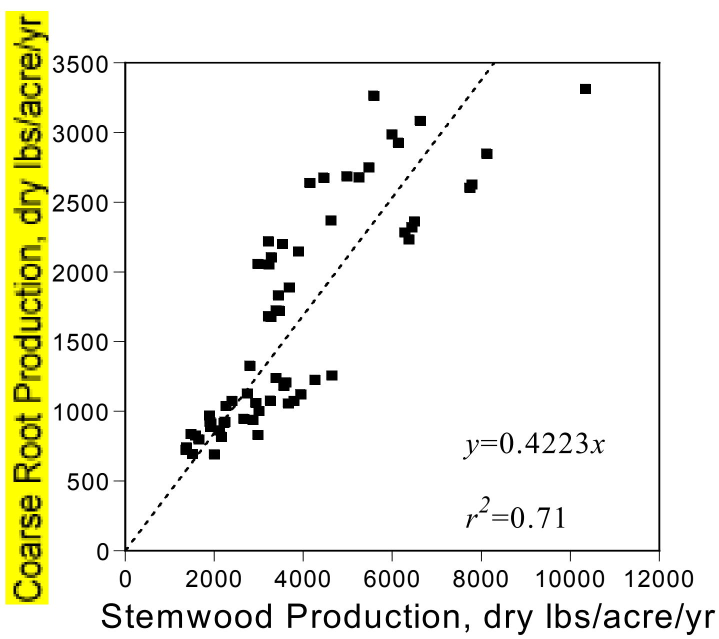

Figure 14. Relationship between total coarse root production, including taproots, and stemwood production at SETRES, 1992-1995.

As discussed below, the relationship of production at the leaf level to total stemwood production can be highly sensitive to partitioning of photosynthate to woody tissues outside the stem. This area remains a key research concern and additional data and information will be introduced to the model as they become available.

Foliage and fine root construction

Calculation of foliage and fine root construction takes place after calculation of the production of all other tissues, and involves the simultaneous solution of two nonlinear equations. The first equation describes the relationship between leaf area index and either net carbon fixation or stemwood production. The second equation describes the functional balance between foliar biomass and fine root biomass. Because woody tissue construction and foliar biomass produced during the previous year are known, these two equations complete the description of tissue production within the stand during the growing season.

The default method of specifying production relies on a simple linear relationship between leaf area index and total stemwood volume production, as suggested by a range of studies in a variety of coniferous species (Albrektson *et al.* 1977, Binkley and Reid 1984, Magnussen *et al.* 1986, Teskey *et al.* 1987, Vose and Allen 1988):

$$\Delta V_{gross} = p_o \, \mathrm{LAI} \qquad (3a)$$

Vose and Allen (1988) indicate that the value of p_0 is about 100 ft^3/acre/yr per unit LAI. This relationship does not impose a maximum value on *LAI* or on total production.

To facilitate crossover between process models and empirical growth and yield and nutrition calculations, an alternate method of specifying total production is available. Results obtained using the process model BIOMASS (NCSFNC 1996) indicate that

across the range of loblolly pine plantations in the Southeast, maximum rates of net carbon assimilation range from 10,000 to 15,000 lbs C/acre/yr. These maximum rates of assimilation correspond to an optimal *LAI* in the range of 3.5-4.5. *NUTREM* allows the user to specify a maximum net assimilation rate and optimal LAI. Using these specified rates, the assimilation/leaf area index curve is approximated using a simple quadratic function, as suggested by more detailed model results (NCSFNC 1996):

$$A_{net} = p_1 \text{LAI} + p_2 \text{LAI} \qquad (3b)$$

where A_{net} is net assimilation and p_1 and p_2 are parameters calculated directly from optimal *LAI* and maximum net assimilation. Because total tissue construction (including foliage and fine roots) must balance net assimilation, this relationship provides an alternate method of constraining tissue construction. In general, results obtained using this method are highly sensitive to the optimal LAI, the maximum assimilation rate, and the partitioning coefficients for the woody tissues. Furthermore, because a definite maximum for tissue construction exists, an exact carbon balance may be impossible for some growth scenarios. In operation, the model continues to provide estimates for these conditions, but prints a warning message. In general, we recommend specifying production in this way only for advanced users who are prepared to deal with the implications of the production physiology.

Regardless of the choice of production function used, *LAI* is calculated internally as

$$\text{LAI} = (0.9/2800)\,[(1\text{-}\Phi)\,\chi_{foliage,\,t\text{-}1} + (1\text{+}\Phi)\,\chi_{foliage,\,t}\,] \qquad (4)$$

where $x_{foliage,\,t}$ represents the construction rate of foliage during year t in lbs/acre/yr. The factor 0.9 converts production to peak leaf area, while 2800 is the dry weight per acre per unit LAI in lbs. The factor ϕ represents a damping factor which is calculated each year according to the following method. During the first year of the model, or immediately following a thinning, ϕ is set to 1.0. This has the effect of calculating leaf area based solely on the current year's foliage production. During most years, ϕ is set to a small value, by default 0.5. This leads to a leaf area estimate based in an unequal way on two years' production. Setting ϕ to 0.0, which would lead to equal weighting, leads inevitably to numerical instability and wild oscillations in the model. This type of behavior is common to models which attempt to track individual foliage cohorts; the use of ϕ in this model reflects a compromise between strict realism and appropriate mathematical behavior.

$$x_{fine\ root,\ t} = c_t \frac{r_0 r_1}{r_1 + \left(x_{foliage,\ t-1} + x_{foliage,\ t}\right) / c_t}$$

The second equation which is required to fully specify the tissue construction rates is a functional balance between total foliar biomass (as calculated from two years of foliage production) and fine root biomass. Despite the importance of fine root turnover to the overall nutrient balance, very little data exists from which to parameterize this relationship. The relationship for the SETRES site is shown in Figure 16. The fine root-foliar balance is represented in the model as where $x_{i,t}$ represents the construction rate of tissue i during year t, and c_t represents the fractional crown coverage during year t. The parameters r_0 and r_1 are estimated from the data. Crown rise is simulated based on *TPA*

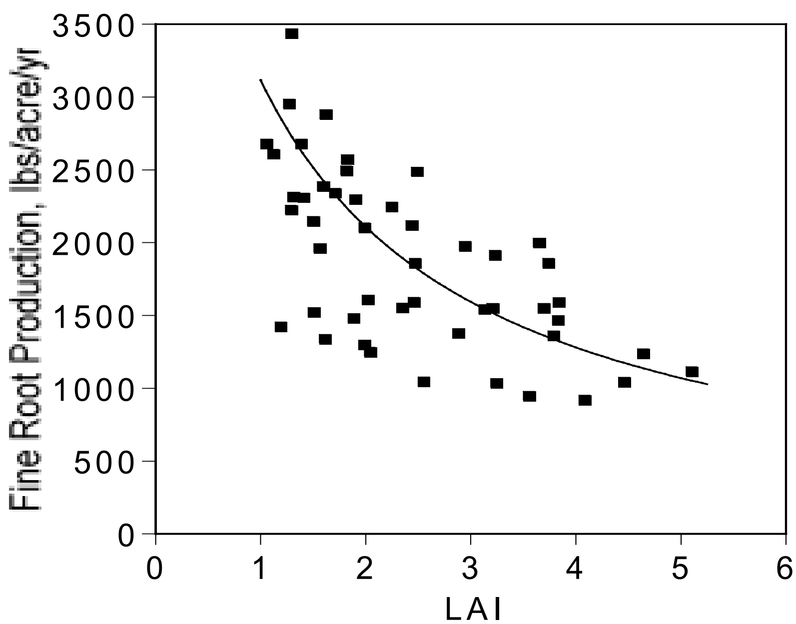

Figure 16. Relationship between fine root production and LAI at SETRES. Reference line shows the full crown occupancy relationship for r_0=5970, r_1=3400.

and H using the methods described by Valentine *et al.* (1994) and used to calculate fractional crown coverage. Because the equations in Valentine *et al.* (1994) do not include nutrient limitation to crown size, fractional crown coverage should be considered as potential rather than actual. Equations 3*a* or 3*b* and 4 are solved iteratively using Newton's method (Press *et al.* 1992).

Nutrient uptake and removal rates

Once the construction rates for all tissues have been solved for all years, nutrients used for construction are calculated based on fixed tissue nutrient concentrations. Tissue nutrient concentrations are calculated proportionally to foliar nutrient concentration, using the concentrations observed at SETRES (Albaugh *et al.* 1998). Estimated removals at the end of the rotation are based on calculated stemwood and foliar biomass, and on branch biomass as estimated using the total branch biomass equation of Shelton *et al.* (1984). Removals during thinnings are calculated proportionally to trees removed, *i.e.* all thinnings are treated as row thinnings for nutrient removal purposes.

Example outputs and implications

Two scenarios for TAUYIELD model

For demonstration purposes, we present a series of scenarios generated using TAUYIELD model, a stand-level growth and yield model for thinned and unthinned loblolly pine plantations, developed by Department of Forestry, Virginia Polytechnic and State Institute. TAUYIELD was developed around three dynamic equations that project stand future attributes: height-age (SI), survival, and basal area. (Amateis et al. 1996). We simulated two scenarios (Table 8). The output from each scenario was input into *NUTREM 2.0* for nutrient uptake and harvest removals estimation. These scenarios were not designed to capture any operational silvicultural regime exactly; rather, they illustrate the range of behavior that can be expected from the model.

Table 8. Example scenarios. All simulated stands were located in the lower coastal plain. Initial survival was set at 100%; stands were simulated through year 25.

Scenario	Site Index (ft, age 25)	Initial Density (trees/ac)	Thinning Regime
A	70	800	none
B	70	800	Row thin at age 15, leave 300 trees/ac

The net growth, soil nutrient uptake, and harvest removal at year 25 calculated by *NUTREM 2.0* for scenario A were shown in Figures 17, 18, and 19 respectively. Similarly, scenario B outputs were shown in Figures 20, 21, and 22 respectively. In general, neither of two scenarios indicate any volume growth before age 8, reflecting the measurement and estimation procedures used by TAUYIELD model. Note that initial changes in growth following thinning for the two thinned scenarios do not correspond well to the trees per acre removed. For example, in scenario B, only 38% of the trees remained after the row thinning at age 15. However, gross volume increment drops only to 58% of its prethinning value. To achieve these results in a real stand, either leaf area efficiency would have to double immediately after thinning, or the stand would be required to invest heavily in new foliage production. This behavior is critical to understanding the soil uptake profiles as described below. Interestingly, the gross increment for the thinned scenarios remains depressed below the unthinned scenarios for the remainder of the rotation. This implies that, after a rapid but partial recovery, foliage production in these older thinned stands never regains the levels seen before thinning or in identical but unthinned stands.

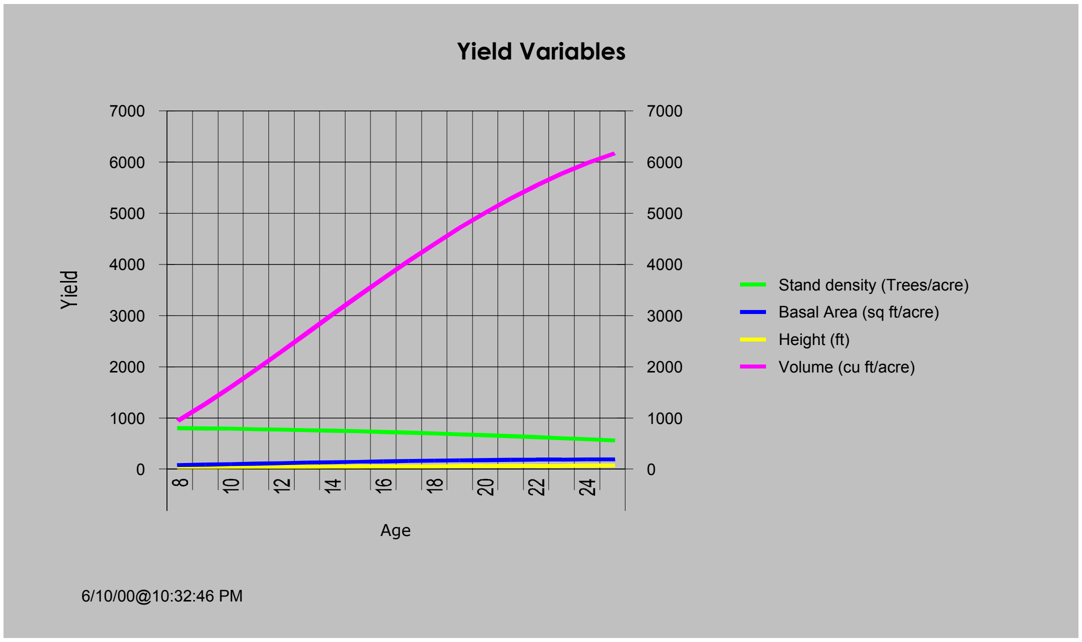

Figure 17. Stand yield of loblolly pine plantation with initial density of 800 trees/acre and site index of 70 without any thinings

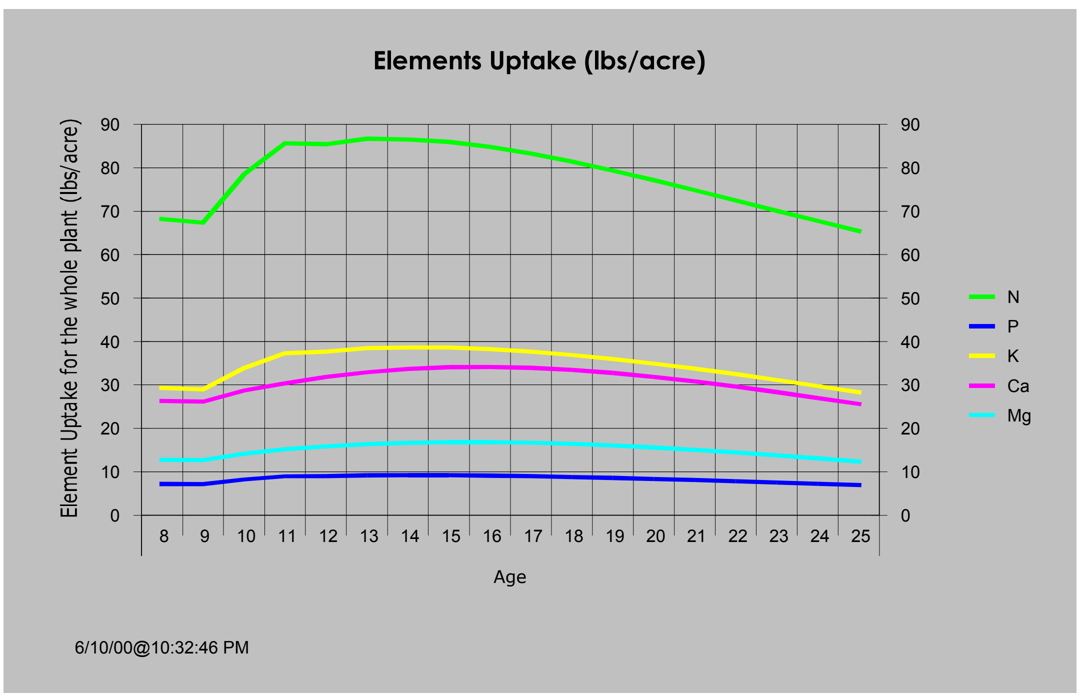

Figure 18. The uptakes of soil nutrient N, P, K, Ca, and Mg for the plantation with ST=70 and initial density of 800 trees/care

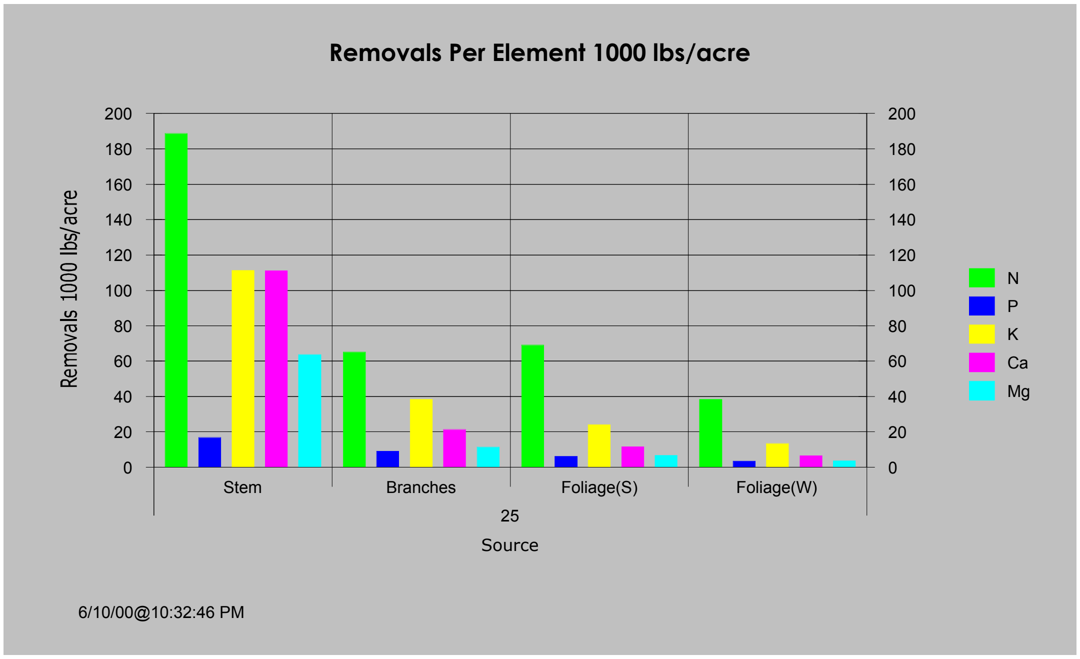

Figure 19. The harvest removals of soil nutrient N, P, K, Ca, and Mg at year 25 with ST=70 and initial density 800 trees/care without any thinings.

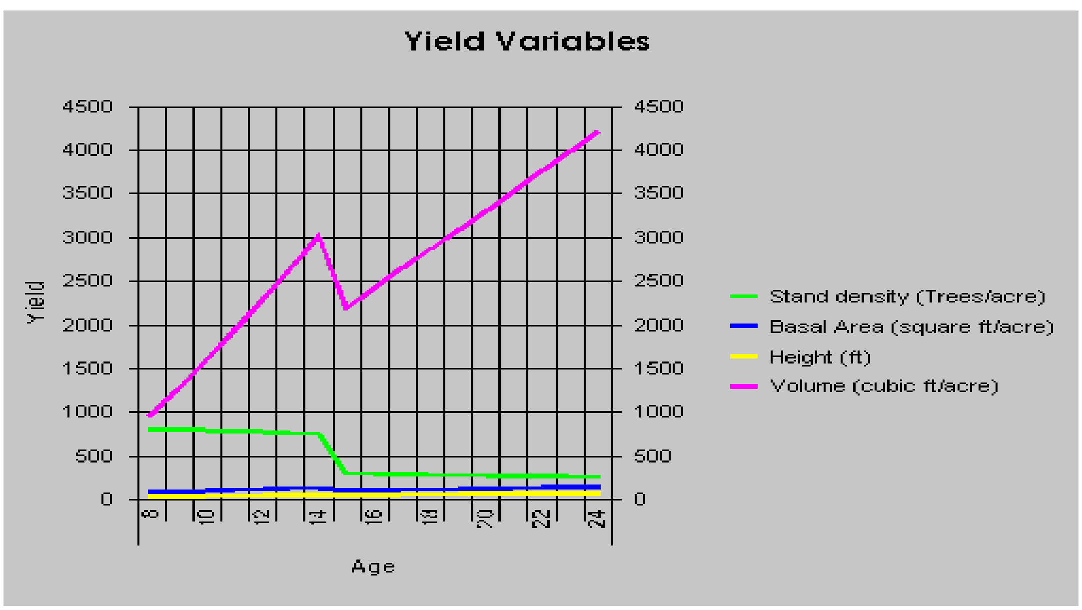

Figure 20. Stand yield of loblolly pine plantation with initial density of 800 trees/acre and site index of 70, thinned to 200 trees/acre at year 15

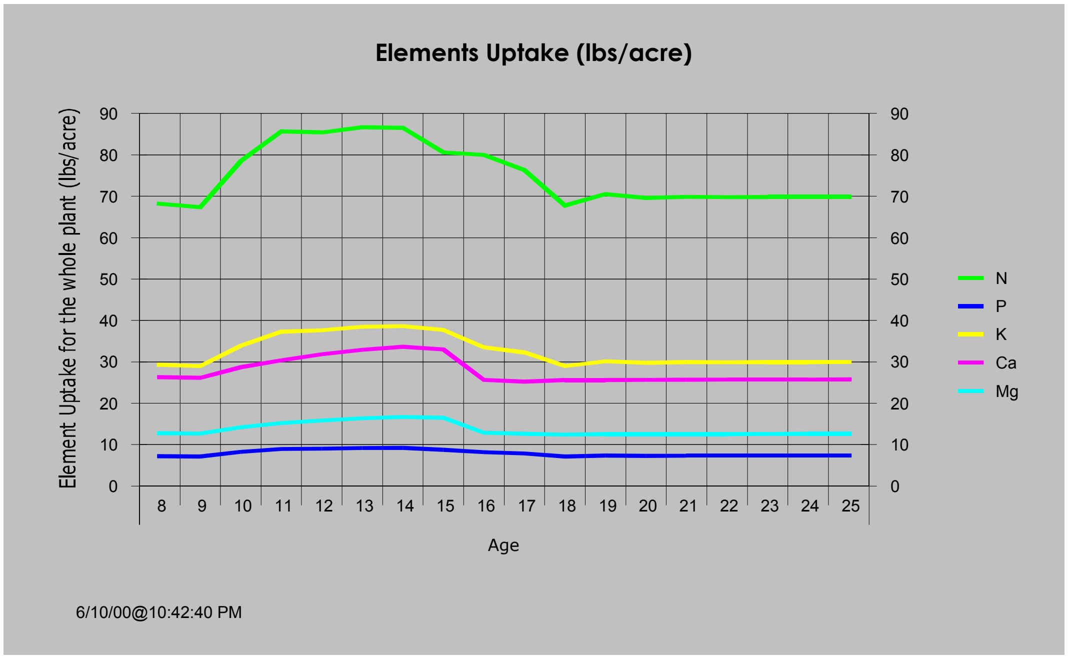

Figure 21. The uptakes of soil nutrient N, P, K, Ca, and Mg for the plantation with ST=70 and initial density of 800 trees/care, thinned to 200 trees/acre at year 15

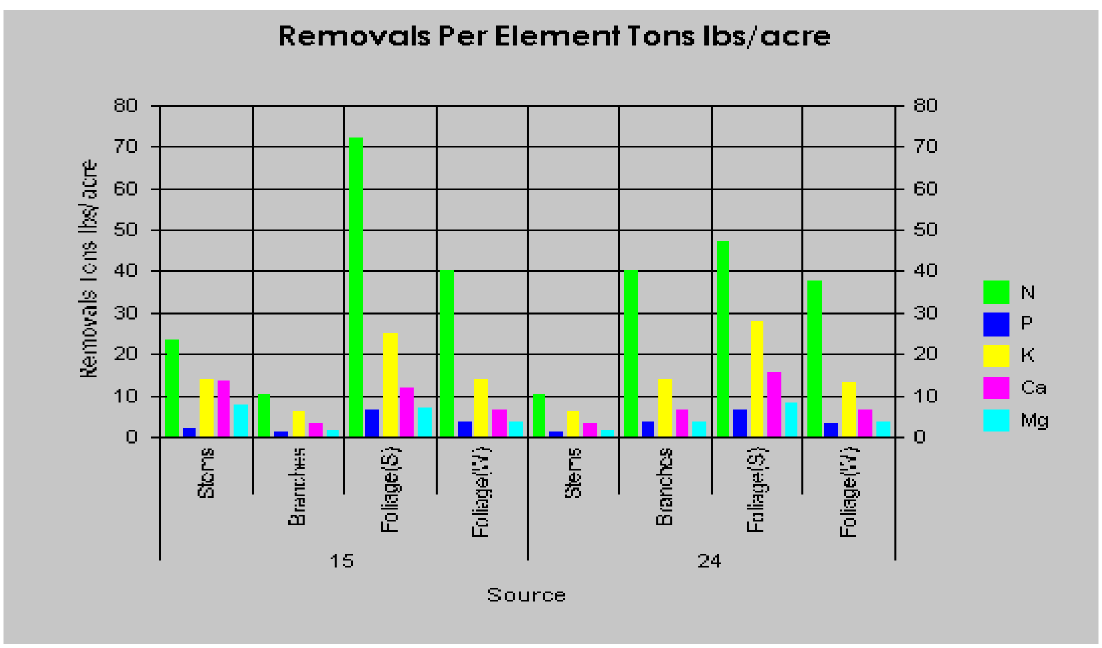

Figure 22. The harvest removals of soil nutrient N, P, K, Ca, and Mg at year 25 with ST=70 and initial density 800 trees/care, Thinned to 200 trees/acre at year 15.

Model simulation for Henderson site productivity study

NUTREM 2.0 was used to estimate soil nutrient uptake and nutrient pools of stem, branch, and foliage of loblolly pine plantations at year 16 for the treatments of chop and burn (CHNO) and shear, pile and vegetation control (DIHR) (NCSFNC 1994). The yearly biomass production, soil nutrient uptake, soil nutrient pools at year 16 for CHNO as calculated by *NUTREM 2.0* were showed in figure 23, 24, and 25. Similarly, the outputs were provided for the treatment of DIHR in figure 26, 27, and 28.

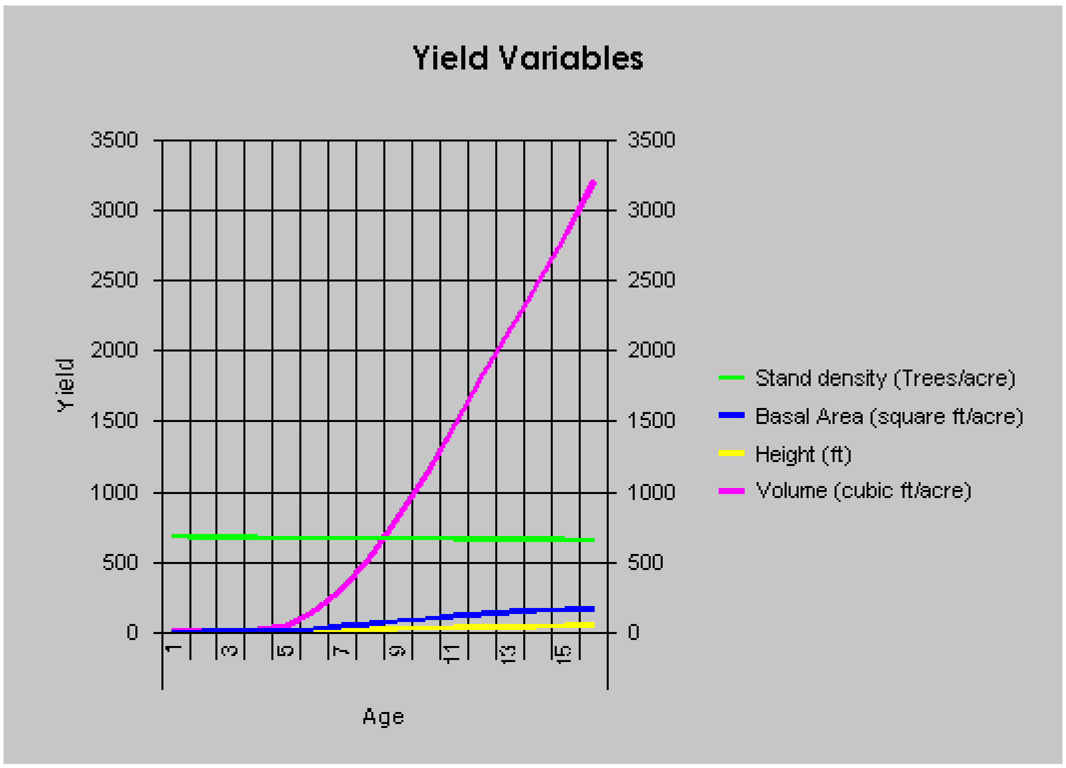

Figure 23. Plantation biomass production with CHNO treatment

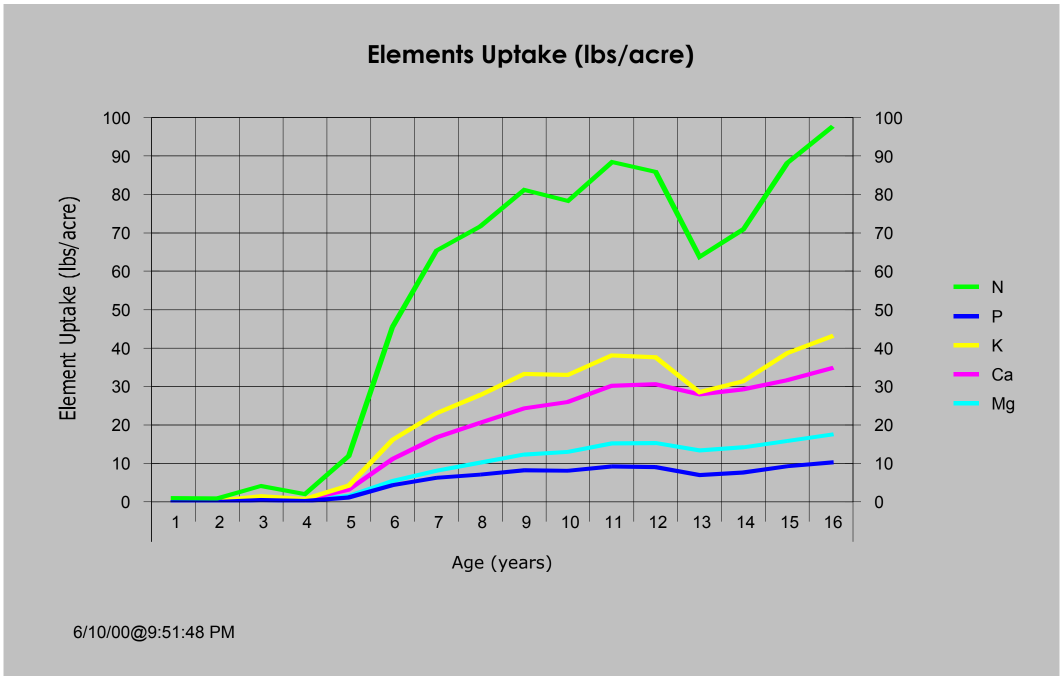

Figure 24. Soil uptakes of nutrient N, P, K, Ca, and Mg for the plantation with CHNO treatment

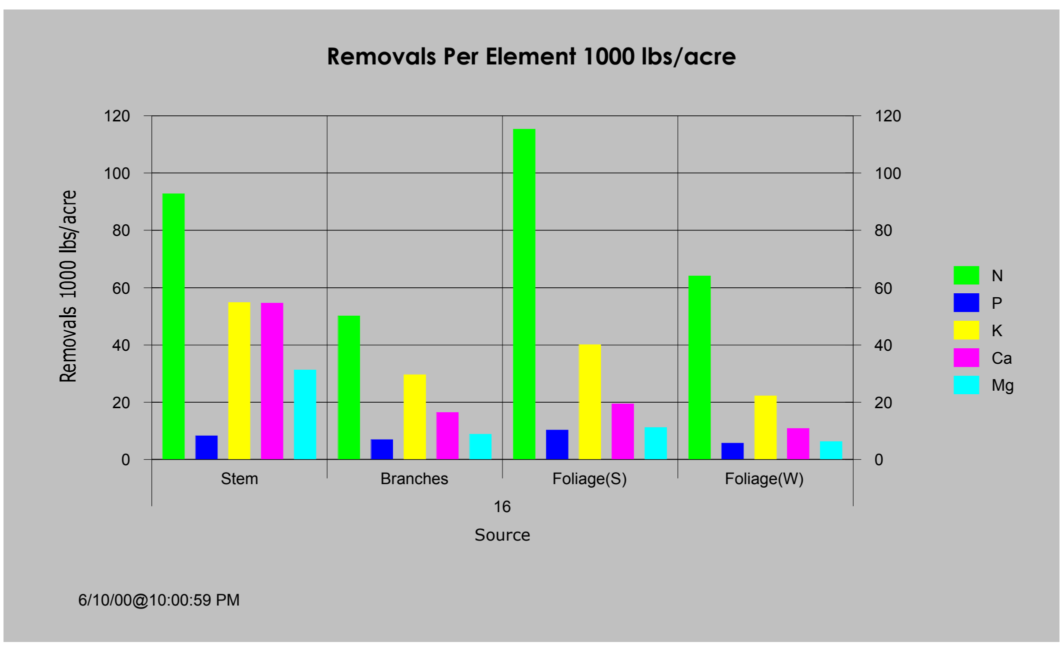

Figure 25. The storage pools of nutrient N, P, K, Ca, and Mg in stem, branch, and foliage at year 16 with CHNO treatment .

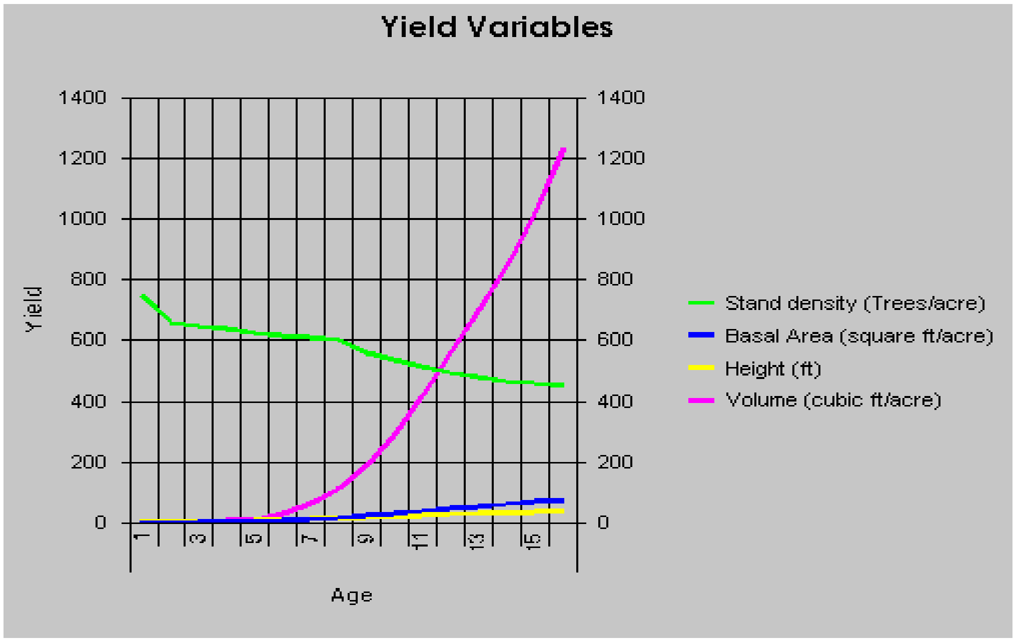

Figure 26. Stand yield of plantations with DIHR treatment

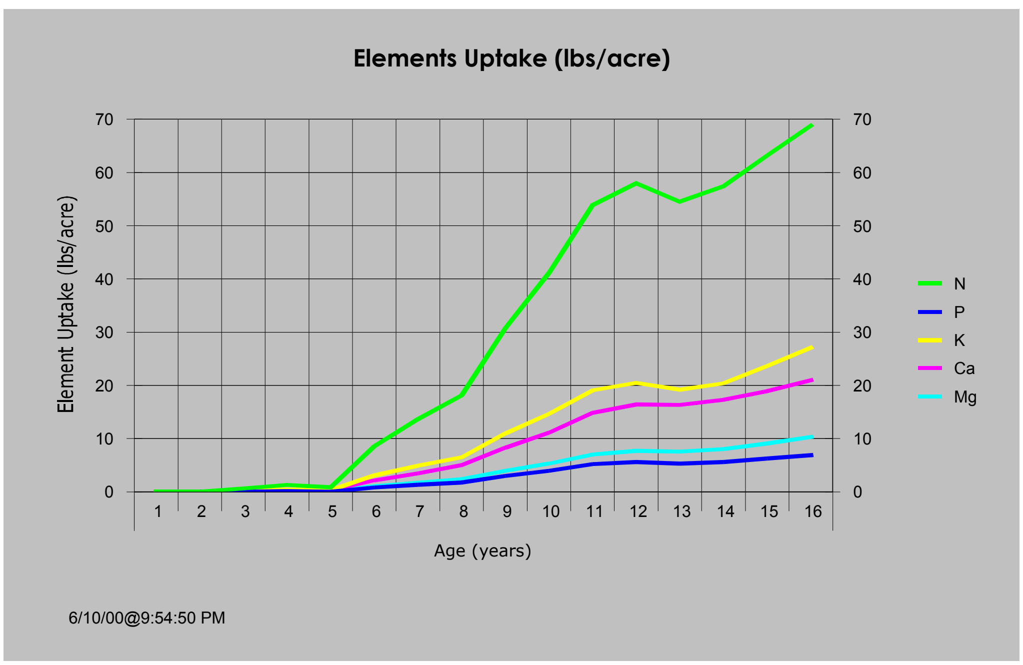

Figure 27. Soil uptakes of nutrient N, P, K, Ca, and Mg for the plantation with DIHR treatment

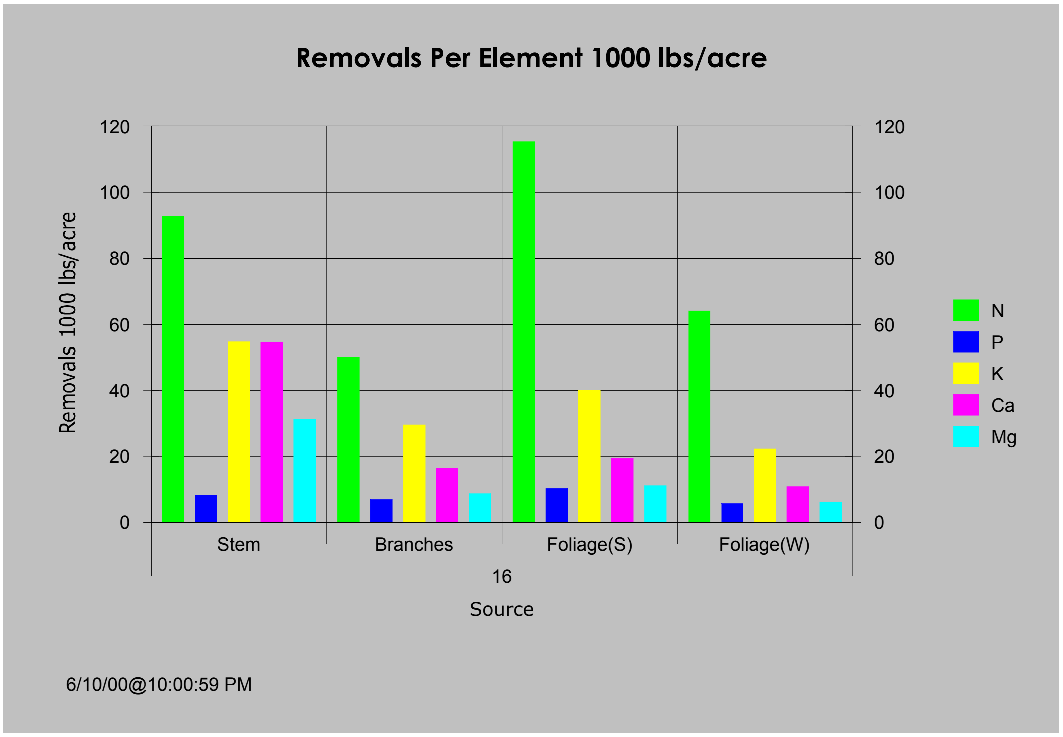

Figure 28. The storage pools of nutrient N, P, K, Ca, and Mg in stem, branch, and foliage at year 16 with DIHR treatment **.**

Results for nutrient utilization and implication

Not surprisingly, the soil nutrient uptake for the four scenarios, two from TAUYIELD model and two from Henderson site Productivity study, roughly paralleled gross cubic volume increment. However, differences in the exact form of the uptake curves can be seen between N, P, and K, for which retranslocation is a major source, and Ca and Mg, for which retranslocation is negligible.

Dynamics of uptake in the thinned scenario reflected the patterns of gross growth implied by the growth and yield projection. Because gross growth immediately following thinning was greater, on a proportional basis, than the foliage remaining following thinning, the stand must grow a large foliage cohort in the year following thinning. However, because growth rates remain relatively constant thereafter, a smaller cohort is required the following year. This pattern of alternating years of high and low foliage growth, accompanied by a complementary pattern of increased and decreased retranslocation following the foliar senescence, decays exponentially and is responsible for the visible oscillations in the model output.

While the pattern of nutrient uptake does approximate the pattern of gross increment, there are important differences with biological and silvicultural implications. First, the relationship is clearly not a unified straight line as would be expected from a simple conversion factor approach. Instead, there is a considerable hysteresis effect superimposed on a mild nonlinear relationship. The hysteresis reflects the differences in soil nitrogen requirements when leaf area is increasing and when it is decreasing. When leaf area is increasing, the amount of nitrogen available from retranslocation is low relative to construction requirements, because the senescing foliage cohort is smaller than the foliage cohort being constructed. This means a larger portion of the requirements must come from the soil. Conversely, when leaf area is decreasing, retranslocation is large relative to construction requirements, and nutrient uptake from the soil is reduced. Silviculturally, this indicates that stands which have fallen behind optimal production will require larger nutrient amendments to increase production to a target level than will stands which have been maintained at high levels. It also suggests that peak nutrient uptake rates may precede culmination of current annual stemwood increment.

Model limitations

While *NUTREM* synthesizes the results of a large number of studies, it has limitations. These limitations can be grouped into two general areas: data limitations and process limitations. First, for many of the functional relationships in the model, the only extant source of data is the SETRES study. We expect this shortcoming to be remedied over time as additional studies, such as the Regionwide 18 installations, provide opportunities for corroborating or revising these relationships. However, until such data become available, the specific numbers produced by the model should be regarded as more approximate than the overall patterns.

Second, many processes do not appear in the model. For example, *NUTREM* does not address the impacts of site preparation on nutrient stocks, which can be substantial (Neary *et al.* 1984, Tew *et al.* 1986). Thus, relying solely on *NUTREM* to provide an estimate of rotation-length silvicultural systems on site nutrient capital could prove misleading. For many processes, such as shifts in allocation to branches and coarse roots with changes in stand structure, and changes in tissue concentrations with improved nutrition, data are simply not available to begin constructing functional relationships. Here, again, studies such as Regionwide 18 will prove invaluable.

Finally, *NUTREM* as presently formulated does not include competing vegetation. Thus, predicted uptake rates should be construed as relating only to the loblolly component of the stand, and removals should not be interpreted to include those associated with hardwoods or the elimination of herbaceous vegetation. Where such removals are expected to be important, *NUTREM* will still provide a good estimate of the loblolly component.

Literature cited

Albaugh, T. J., H. L. Allen, P. M. Dougherty, L. W. Kress, and J. S. King. 1998. Leaf area and above- and belowground growth responses of loblolly pine to nutrient and water additions. To appear in *Forest Science*.

Albrektson, A., A. Arronsson, and C.O. Tamm 1977. The effect of forest fertilization on the primary production and nutrient cycliing in the forest ecosystem. Silva Fenn. 11:223-239.

Binkley, D. and P. Reid. 1984. Long-term responses of stem growth and leaf area to thinning and fertilization in a Douglas-fir plantation. *Canadian Journal of Forest Research* 14: 656-660.

Byram, T. D., and Lowe, W. J. 1988. Specific Gravity variation in a Loblolly pine Seed Source study in the Western Gulf region. For. Sci. 34: 798-803.

Clutter, J. L. 1963. Compatible growth and yield models for loblolly pine. *Forest Science* 9: 354-371.

Francis, J. K. and J. B. Baker. 1982. Potential for nutrient depletion by short rotation harvest of sweetgum. *Soil Science Society of America Journal* 46(5); 1116-1118.

Haynes, B. E., and S. T.Gower. 1995. Belowground carbon allocation in nonfertilized and fertilized red pine plantation in northern Wisconsin, Tree Phys. 15:317-325.

Keyes, M. R., and C.C. Geirer. 1981. Above-and below-ground net production in 40 year-old Douglas-fir stands on low and high productivity sites. Can. J. For. Res. 11:599-605.

Johnson, D. W., D. Binkley, and P. Conklin. 1995. Simulated effects of atmospheric deposition, harvesting, and species change on nutrient cycling in a loblolly pine forest. *Forest Ecology and Management* 76: 29-45.

Lockaby, B. G. and J. C. Adams. 1986. Dry weight and nutrient content of fuelwood biomass from loblolly pine stands in North Louisiana. *Forest Science* 32(1); 3-9.

Magnussen, S., V. G. Smith, and C. W. Yeatman. 1986. Foliage and canopy characteristics in relation to aboveground dry matter increment of seven jack pine provenances. *Canadian Journal of Forest Research* 16: 464-470.

Mann, L. K., D. W. Johnson, D. C. West, D. W. Cole, J. W. Hornbeck, C. W. Martin, H. Riekerk, C. T. Smith, W. T. Swank, L. M. Tritton, and D. H. van Lear. 1988. Effects of whole-tree and stem-only clearcutting on postharvest hydrologic losses, nutrient capital, and regrowth. *Forest Science* 34(2): 412-428.

NCSFNC, 1996. Climate and soil water holding capacity effects on carbon assimilation by loblolly pine stands—a modeling analysis. Forest nutrition cooperative, department of forestry, North Carolina State University, Raleigh, NC.

Neary, D. G., L. A. Morris, and B. F. Swindel. 1984. Site preparation and nutrient management in southern pine forests. pp. 121-144 *in* E. L. Stone, ed. *Forest Soils and Treatment Impacts.* Knoxville: University of Tennessee.

North Carolina State Forest Nutrition Cooperative (NCSFNC). 1994. Performance of loblolly pine site index equations in midrotation plantations. Raleigh, NC: North Carolina State University, College of Forest Resources, NCSFNC Research Note 10.

North Carolina State Forest Nutrition Cooperative (NCSFNC). 1996. Climate and soil water holding capacity effects on carbon assimilation by loblolly pine stands -- a modeling analysis. Raleigh, NC: North Carolina State University, College of Forest Resources, NCSFNC Research Note 12.

Patric, J. H. and W. M. Smith. 1975. Forest management and nutrient cycling in eastern hardwoods. U.S.D.A. Forest Service, Northeastern Forest Experiment Station, Research Paper NE-324. 23 pp.

Plantation Management Research Cooperative (PMRC). 1996. Yield prediction and growth projection for site-prepared loblolly pine plantations in the Carolinas, Georgia, Alabama, and Florida. Athens, GA: University of Georgia, Daniel B. Warnell School of Forest Resources, PMRC Tech. Report 1996-1.

Press, W. H., S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery. 1992. *Numerical Recipes in C*, 2d ed. Cambridge, UK: Cambridge University Press. 994 pp.

Shelton, M. G., L. E. Nelson, and G. L. Switzer. 1984. The weight, volume and nutrient status of plantation-grown loblolly pine trees in the interior flatwoods of Mississippi. Mississippi Agricultural and Forest Experiment Station, Technical Bulletin 121. 27 pp.

Switzer, G. L. and L. E. Nelson. Nutrient accumulation and cycling in loblolly pine (*Pinus taeda* L.) plantation ecosystems: the first 20 years. *Soil Sci. Soc. Am. Proc.* 36: 143-147.

Switzer, G. L., L. E. Nelson, and L. E. Hinesley. 1978. Effects of utilization on nutrient regimes and site productivity. pp. 91-102 in *Complete Tree Utilization of Southern Pine*. Madison, WI: Forest Products Research Society.

Tew, D. T., L. A. Morris, H. L. Allen, and C. G. Wells. 1986. Estimates of nutrient removal, displacement and loss resulting from harvest and site preparation of a *Pinus taeda* plantation in the Piedmont of North Carolina. *Forest Ecology and Management* 15: 257-267.

Valentine, H. T., A. R. Ludlow, and G. M. Furnival. 1994. Modeling crown rise in even-aged stands of Sitka spruce or loblolly pine. *Forest Ecology and Management* 69: 189-197.

Van Lear, D. H., J. B. Waide, and M. J. Teuke. 1984. Biomass and nutrient content of a 41-year-old loblolly pine (*Pinus taeda* L.) plantation on a poor site in South Carolina. *Forest Science* 30: 395-404.

Van Lear, D. H., W. T. Swank, J. E. Douglass, and J. B. Waide. 1983. Forest management practices and the nutrient status of a loblolly pine plantation. U.S.D.A. Forest Service, Pacific Northwest Forest and Range Experiment Station, Gen. Tech. Rpt. PNW-163: 252-258.

Vose, J. M. and H. L. Allen. 1988. Leaf area, stemwood growth, and nutrition relationships in loblolly pine. *Forest Science* 34: 547-563.

Wells, C. G. and J. R. Jorgensen. 1975. Nutrient cycling in loblolly pine plantations. pp. 137-157 in B. Bernier and C. H. Winget, eds. *Forest Soils and Land Management*. Montreal: Laval University Press.

Wells, C. G. and J. R. Jorgensen. 1977. Nutrient cycling in loblolly pine: silvicultural implications. *TAPPI* 61: 29-32.

Zhang, S. and H. L. Allen, 1996. Foliar nutrient dynamics of 11 year-old loblolly pine (*pinus teada*) following nitrogen fertilization. Can. J. For. Res. 26: 1426-1439.

Zobel, B. J., R. C. Kellison, M. F. Matthias, A. V. Hatcher, 1996. Wood desnity of southern pines. North Carolina Agricultural Experiment Station, Tech. Bul. No. 208, North Carolina State University.