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Title: A Model of Forest Nitrogen Cycling to Assess the Effects of Management Intensity on Long-Term Productivity in Douglas-fir Forests of the Pacific Northwest

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The objective of this study was to assess the effects of forest management intensity on long-term productivity of Pacific Northwest Douglas-fir forests. The components of management intensity included rotation length, timber utilization standard (whole tree or bole only), method of slash treatment (remove/burn or leave) and fertilization practice (urea nitrogen fertilization or red alder crop rotations).

A computer simulation model of forest nitrogen cycling and growth was developed. Long-term forest productivity was indicated by trends in the following variables over time: forest floor and total soil nitrogen; nitrogen in the Douglas-fir and understory vegetation; nitrogen losses from vegetation removal and slash treatment; and Douglas-fir timber volumes (both standing volume and volume removed by harvesting).

A range of 15 management prescriptions were simulated for a 360-year period. The results indicated that the development of the Douglas-fir stand caused a steady decline in total soil nitrogen. Shorter rotation lengths, 50-60 years, produced more rapid depletions of soil nitrogen than longer, 120-year rotations. Whole tree harvesting with 60-year rotations, slash removal and no fertilization caused a 130 percent increase in the amount of soil nitrogen required over the 360 years, compared to harvesting boles only. The addition of urea fertilizer increased wood and bark volumes by 15 percent, while decreasing the soil nitrogen requirements of whole tree harvesting by 14 percent. The use of 15 and 40-year alder rotations caused 11 and 12 percent increases, respectively, in subsequent Douglas-fir volumes, while decreasing total soil nitrogen requirements by 60 to 72 percent compared to urea fertilization.

Slash removal practices resulted in a 23 percent increase in the average soil nitrogen requirement per 60-year rotation, in combination with whole tree harvesting and no fertilization. Harvesting of boles only lessened this effect of slash removal on soil nitrogen requirements.

The research results indicate that forest managers and decision makers can no longer make the unqualified assumption that growth rates will be maintained or increased as management intensity

increases. The simulated levels of soil nitrogen depletion after 360 years of management show that the assumed growth rates would not be maintained over this long a time period.

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A Model of Forest Nitrogen Cycling to Assess the Effects of Management Intensity on Long-Term Productivity in Douglas-Fir Forests of the Pacific Northwest

by

Joan Krzak

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I. INTRODUCTION

A. Problem Statement

The long time period associated with the management of forest resources causes current management decisions to be based on projections of future forest conditions. These projections depend on estimates of the long-term productivity of forest land. Long-term productivity refers to the potential for the land, over at least the next several hundred years; to produce tree growth at consistently high levels without significant reduction in the quality of soil or water resources. Therefore, long-term productivity has two interrelated components. The first, more conventionally defined component is tree volume growth. The second component concerns the less easily defined aspects of an ecosystem's productive capacity, namely the soil and water resources. Projections of both components of long-term productivity are critical to forest management decision analyses.

In managed forests, there are many opportunities to influence future productivity through land management practices. Forest fertilization, for example, can increase productivity in Douglas-fir (_Pseudotsuga_ _menziesii_ (Mirb.) Franco) forests of the Pacific Northwest

(Turnbull and Peterson, 1976). In contrast, tractor logging practices may contribute to soil compaction and potential declines in long-term productivity (Froehlich, 1979). Hence, long-term productivity is a dynamic concept, dependent on the timing and nature of forest management practices.

The decision maker's needs to assess future tree growth and soil and water quality, combined with the dynamic nature of long-term forest productivity, create the problem of estimating productivity trends. For example, this problem is evident in the determination of timber sustained yield harvest levels. The Multiple Use-Sustained Yield Act of 1960 provided for the sustained yield management of national forest renewable resources. Sustained yield was defined as:

> the achievement and maintenance in perpetuity of a high-level annual or regular periodic output of the various renewable resources of the national forests without impairment of the productivity of the land; (Multiple Use-Sustained Yield Act 1960, emphasis added).

Concern for protection of future productivity was also expressed by the National Forest Management Act of 1976. This act directed the Secretary of Agriculture to promulgate regulations to guide the National Forest System land management planning process in meeting the goals of the Renewable Resource Program which:

> 'insure ... evaluation of the effects of each management system to the end that it will not produce substantial and permanent impairment of the productivity of the land;'

and which

> 'permit increases in harvest levels based on intensified management practices, ... if (i) such practices justify increasing the harvests in accordance with the Multiple-Use Sustained Yield Act of 1960, and (ii) such harvest levels are decreased at the end of each planning period if such practices cannot be successfully implemented or funds are not received to permit such practices to continue substantially as planned;' (National Forest Management Act 1976, sec. 6(g)(3) (c,d), emphasis added).

Consequently, decisions concerning the quantity of timber harvested on a sustained yield basis depend on estimating the effect of management prescriptions[1] on long-term forest productivity. Conventional decision analyses of timber harvest scheduling often assume that increasing timber management intensity results in either increases in future productivity, or at least, maintenance of existing productivity levels.[2] Until recently, these conventional assumptions were seldom questioned for Douglas-fir forests of the Pacific Northwest. But in other forested areas of the United States, recent work in forest nutrient cycling models has indicated a possibility of soil nutrient depletion and resulting long-term productivity decline with successive forest rotations and with increasing timber

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[1] A forest management prescription consists of a set of management practices designed to produce specific forest outputs. For example, a high intensity timber management prescription might include the following management practices: planting, precommercial and commercial thinning, fertilization, clearcut harvesting.

[2] For an example, see Beuter, Johnson and Scheurman, 1976.

utilization standards[3] (Penning de Vries, Murphy, Wells and Jorgensen, 1975; Waide and Swank, 1977; Swank and Waide, 1980; Aber, Botkin and Melillo, 1979). These predictions open up the question of whether similar productivity declines are possible with management of Douglas-fir forests in the Pacific Northwest.

Recent literature on forest nutrition of the Douglas-fir region indicates that nitrogen is the forest nutrient often found as limiting in the growth of Douglas-fir (Keeney, 1980; Wollum and Davey, 1975; Gessel, Cole and Steinbrenner, 1973). Therefore, an analysis of the effects of management prescriptions on nitrogen cycling and growth may provide an indication of potential trends in long-term productivity.

B. Research Objective

The research objective was to model forest nitrogen cycling and growth in order to assess the effects of forest management intensity on long-term productivity in Douglas-fir forests of the Pacific Northwest. The process used to meet this objective is described in the next section.

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[3] A forest rotation is the length of time between initial establishment of a stand of trees and its final harvest and regeneration. Timber utilization standards refer to the degree of use of the tree material. For example, harvesting the large branches and the trunks (boles) of trees would constitute a higher utilization standard than one that called for harvesting only the boles.

C. Research Overview

The research process consisted of the following series of steps: The research problem was defined and an objective identified. I then examined the literature to establish a research perspective based on both forest nitrogen cycling and the forest land management planning process. From this the scope of the research was determined and specific research questions identified. The nature of the questions indicated the need for a modeling approach. The next step was to determine the structure of the model. This was followed by a comparison of the scope and model structure with past research and an evaluation of the literature for potential data sources.

After completion of these introductory steps, the model was developed in two stages. The first involved modeling the unmanaged forest; the second stage consisted of the addition of management variables. Validation of the model occurred both during and after model development.

The next step was identification of a range of forest management prescriptions to apply. The model was then used to simulate the effects of the prescriptions on long-term forest productivity. Lastly, I examined the model's deficiencies and strong points and identified the direction for future research.

D. Problem Background

This section identifies long-term forest productivity within the context of both forest land management planning and forest nitrogen cycling. This perspective was then used to determine the scope of the research.

1. The Forest Land Management Planning Process

The national forest land management planning process will result in some critical decisions about the future use of Pacific Northwest timber resources on national forest lands. An important part of this planning process will be the estimation of trends in long-term productivity.

National forest land management planning has three levels: national planning, regional planning and forest planning. The Resources Planning Act of 1974 provided direction for national level planning. This act called for an assessment of the nation's renewable resources and the preparation of a Renewable Resource Program for the "protection, management, and development of the National Forest System" (Forest and Rangeland Renewable Resources Planning Act 1974, sec. 2-3). The national assessment and program are to be updated every ten years. The Resources Planning Act also addressed planning at the forest level by including, as part of the Renewable Resource Program, the development of land and resource management plans for units of the National Forest System (Forest and Rangeland Renewable Resources Planning Act 1974, sec. 5).

In 1976 the Resources Planning Act was amended by the National Forest Management Act. This amendment called for the development of regulations to guide the National Forest System land management planning process. As indicated earlier, the National Forest Management Act made long-term productivity a direct concern of forest planning.

The final planning regulations were released in September of 1979 (USDA Forest Service, 1979). These regulations guide planning at both the regional and the national forest levels. The focus of this study is forest level planning. Prior to the regulations, national forests were engaged in "unit planning," a different concept from "forest planning." The unit planning approach consisted of dividing a national forest into several planning units and then developing a land management plan for each unit. This approach was superceded by the new regulations.

The new forest planning process considers the entire national forest as a "unit" and will result in one land management plan for each forest. The purpose of this plan is to allocate the land to various forest management prescriptions. One of the first steps in the planning process is the estimation of forest land capability. The purpose of a land capability analysis is to assess the productivity potential of the land for various types and intensities of uses. Assessments of land capability for various timber management prescriptions should indicate trends in long-term forest productivity. The land capability information is then used in the estimation of the ecological, social and economic effects of land management alternatives. The capability analysis, then, serves as a basis for future steps in the forest planning process. The estimation of long-term trends in productivity is therefore critical to the forest land management planning and decision-making process.

2. The Forest Nitrogen Cycle

The land's capability for timber production depends on both the management prescription utilized and the availability of adequate sunlight, moisture and nutrients for tree growth. Natural sources of forest nutrients include atmospheric additions in the form of precipitation and dust and additions from mineral weathering. Both of these processes occur at relatively low levels over long time periods. Consequently, nutrients may be an important consideration in analyses of long-term trends in forest productivity. The following section includes a description of forest nitrogen cycling, which provides a basis for the subsequent model. At the same time, the model will include many simplifying assumptions of the "real world" processes.[4]

The forest nitrogen cycle may be considered a system with boundaries at the upper limits of the forest canopy and the lower

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[4] The description of forest nitrogen cycling was compiled from a variety of sources, including Spurr and Barnes, 1980; Miller, Lavender and Grier, 1976; Wollum and Davey, 1975; and personal communications with Cromack, 1979.

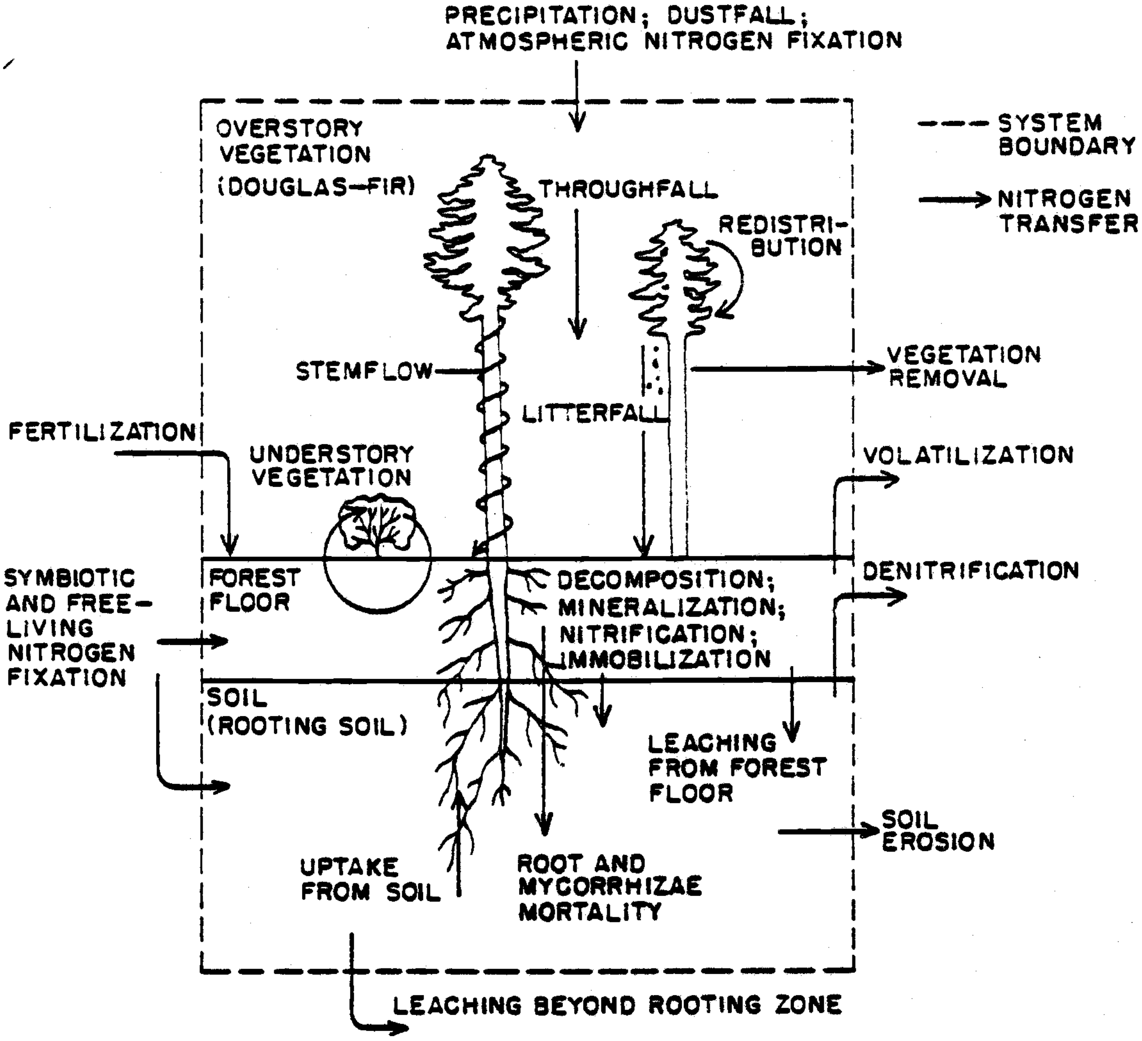
limits of the soil rooting zone. The cycle may then be described by three groups of processes: (1) those associated with nitrogen additions to the system; (2) processes internal to the system; and (3) those associated with losses of nitrogen from the system.

Figure 1 represents the forest nitrogen cycle. Nitrogen occurs in several different forms in this system. Ammonium nitrogen (NH_4^+) and nitrate nitrogen (NO_3^-) are the two most common forms potentially available for use by forest vegetation. Organic nitrogen is the nitrogen incorporated in living and dead organic matter, e.g., the nitrogen in amino acids. Recent literature indicates that amino acid nitrogen may also be utilizable by the vegetation (Powell _et al_., 1980; Harley, 1969).

The forest nitrogen cycle differs from that of other nutrients since the primary source is the atmosphere, rather than from mineral weathering. Atmospheric inputs of nitrogen include precipitation, dustfall and nitrogen fixation. Precipitation input is usually divided into throughfall, which passes through the canopy to the forest floor, and stemflow, which flows down the boles of trees. Both forms may be enriched in nitrogen as dust and other particulate matter is washed from the foliage and boles, or as nitrogen is leached directly from the foliage. Additions from precipitation and dust are usually in the form of ammonium, nitrate and organic nitrogen.

The second process associated with nitrogen inputs is

FIGURE 1. Forest Nitrogen Cycling.



fixation. Nitrogen fixation is the conversion of nitrogen from the gaseous form (N_2) to forms which can be readily used by green plants. This can occur through both atmospheric and biological nitrogen fixation. Atmospheric fixation by lightning and volcanism converts gaseous nitrogen to nitrate nitrogen. The nitrate is then dissolved in precipitation. The process of atmospheric fixation seems to occur in only small quantities compared with biological fixation.

Biological nitrogen fixation is the conversion of gaseous nitrogen to ammonium nitrogen by various micro-organisms in both symbiotic and free-living forms. Examples of symbiotic nitrogen fixers include a blue-green alga associated with the lichen Lobaria oregana in Douglas-fir canopies and an actinomycete in the root nodules of red alder trees. There are also free-living microbes in the soil and forest floor which have the ability to fix nitrogen.

The third nitrogen input is the artificial addition of nitrogen through forest fertilization practices. Nitrogen fertilizer is usually applied as urea (46 percent nitrogen) or ammonium nitrate (34 percent nitrogen).

The second group of processes are those internal to the system. A large proportion of the nitrogen in a forest ecosystem is tightly cycled through litterfall, decomposition and subsequent uptake by the vegetation. Litterfall adds foliage, cones, branches, bark and bole wood to the forest floor, with these materials containing organic forms of nitrogen. Root and mycorrhizae[5] mortality also contribute organic nitrogen to the forest floor and to the soil within the rooting zone.

The second internal process, decomposition, is the conversion of organic nitrogen to inorganic forms (ammonium, nitrate) by decomposing organisms in the forest floor and soil. Mineralization occurs when organic nitrogen is converted to ammonium (see Fig. 2). In the presence of nitrifying micro-organisms, the ammonium nitrogen may be oxidized to nitrate by the process of nitrification. Both mineralization and nitrification use up some nitrogen through the respiration of the decay organisms but release inorganic forms that are utilizable by green plants. Immobilization occurs when decay organisms incorporate small amounts of ammonium and nitrate into living and dead organic matter, thus making the nitrogen unavailable for plant uptake.

The third internal process is uptake of nitrogen by the vegetation. Water entering the forest floor leaches the inorganic nitrogen into solution in the forest floor and soil. Most soil nitrogen exists in the organic form, with the available forms comprising only a small part of the total.

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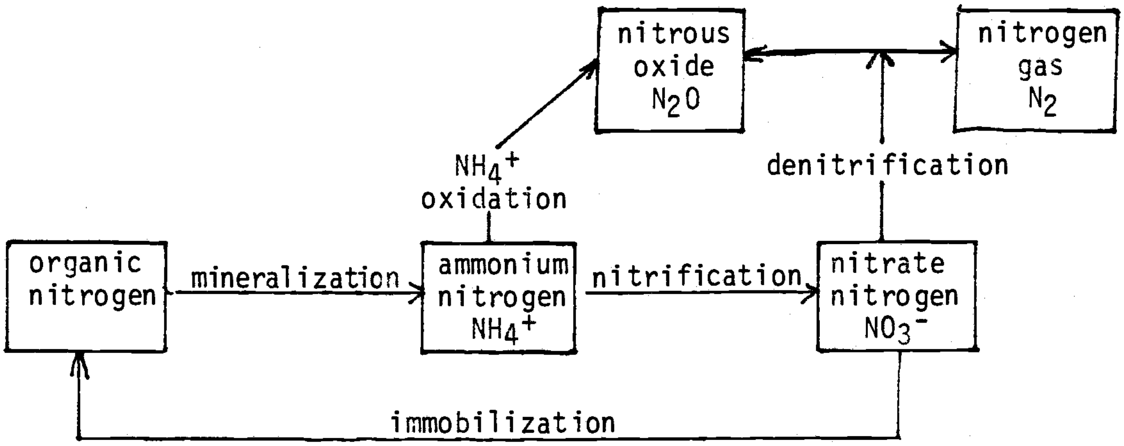
[5] Mycorrhizae are symbiotic associations between fungi and the roots of plants. Mycorrhizae serve to extend the nutrient absorbing capacity of the root system (Harley, 1969, 1975).

FIGURE 2. Nitrogen Transformations in the Forest Floor and Soil



The uptake of available nitrogen from the forest floor and soil occurs by roots and mycorrhizae. A fourth process is the redistribution of nitrogen stored within the tree, for example, from the old foliage to the new.

A third group of processes is associated with losses of nitrogen. One type involves soil erosional processes, which may result in the physical removal of nitrogen from the site. Surface erosion, soil creep, and debris avalanches are examples. Secondly, nitrogen may be leached beyond the rooting zone into subsurface waters and streams. Nitrogen leaching losses are mainly nitrate and organic nitrogen, and to a lesser extent ammonium.

A third process, volatilization, is the loss of nitrogen in gaseous form. This may occur with fires or with application of urea fertilizers in warm, dry weather. There may also be a naturally occurring ammonia (NH_3^+) volatilization loss from the soil, although it has not yet been shown in Douglas-fir forests.[6]

A fourth loss occurs through denitrification, when nitrate is converted to gaseous forms of nitrogen (N_2 or N_2O) by denitrifying bacteria in the soil. Ammonium may also be partially oxidized to nitrous oxide (Bremner and Blackmer, 1979). Fifthly, the physical removal of vegetation and forest floor materials from the site, as in timber harvesting and slash removal, also results in nitrogen losses from the system.

E. Scope of the Research

The problem analysis was followed by my decision of the scope of the model required to meet the research objective. Long-term forest productivity will be indicated by trends over time in the following variables:

1. total soil nitrogen
2. forest floor nitrogen
3. the difference in nitrogen additions to and losses from the system
4. nitrogen losses due to soil leaching, erosion, vegetation removal and slash treatment

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[6] In a stand of red pine (Pinus densiflora) in Korea, Kim (1973) found an average ammonia volatilization of 3.4 kg/ha/week during the months of May through July.

5. nitrogen in the Douglas-fir and understory vegetation
6. Douglas-fir timber volumes (both standing volume and volume removed by harvesting)

Management variables in the model will include:

1. Douglas-fir rotation length (up to a maximum of 120 years)
2. timber utilization standard (whole tree harvesting (excluding roots) or harvesting of boles only)
3. slash treatment (removal--or burning--of 90 percent of the slash or leave slash in place)
4. nitrogen fertilization (urea fertilization or natural fertilization--red alder rotations alternated with Douglas-fir rotations--or no fertilization)

Management intensity is reflected in the choice of management variables. High intensity prescriptions are likely to consist of shorter rotations (50 - 60 years), high utilization standards, slash removal and nitrogen fertilization by urea. Medium intensity prescriptions will generally have longer rotation lengths (70 - 90 years), low utilization standards, and may include slash removal and nitrogen fertilization by urea or red alder. In contrast, low intensity prescriptions will have long rotation lengths (100 - 120 years), low utilization standards, slash left in place after harvesting and may include nitrogen fertilization by alder.

F. Questions Addressed by the Research

The research was designed to answer questions of the following nature:

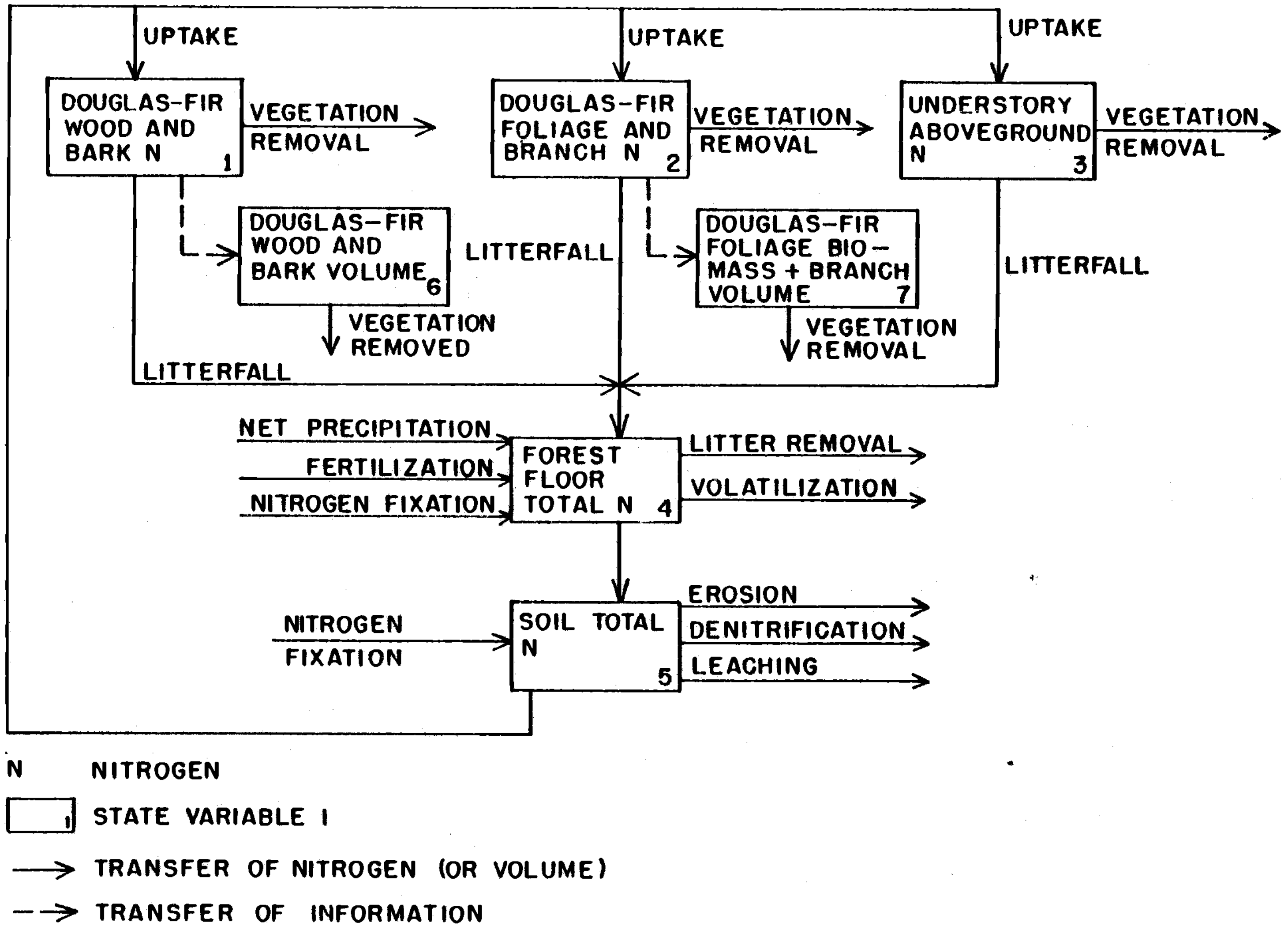
1. What are the long-term trends in soil nitrogen and Douglas-fir timber volumes as management intensity is varied?
2. What effect does the choice of fertilization method (urea nitrogen or red alder) have on timber volumes and soil nitrogen over time?
3. What is the effect of choice of utilization standard on nitrogen losses from the system, on soil nitrogen and on timber volumes?
4. How does the choice of slash treatment affect trends in forest floor and soil nitrogen and nitrogen losses from the ecosystem over time?

G. Structure of the Model

The scope of the research and the nature of the research questions indicated the need for a simulation modeling approach. The structure of the model is represented in Figure 3. Two important features are its annual time resolution and forest stand level of aggregation.

The rectangular compartments in Figure 3 represent state variables, which describe the status of the system at any point in time. The system consists of the aboveground forest vegetation,

FIGURE 3. Model of Long-Term Forest Productivity.



the forest floor and the soil. The model contains the following eight state variables:

State variable	Definition	Units of measurement
X1	Douglas-fir wood and bark nitrogen	kg/ha
X2	Douglas-fir foliage and branch nitrogen	kg/ha
X3	understory aboveground nitrogen	kg/ha
X4	forest floor nitrogen	kg/ha
X5	total soil nitrogen (to a 60 cm depth)	kg/ha
X6	Douglas-fir wood and bark volume	cu ft/ha
X7	Douglas-fir foliage biomass and branch volume	kg/ha cu ft/ha
X8	nitrogen in total aboveground vegetation; X8 = X1 + X2 + X3	kg/ha

The solid arrows represent the flows of nitrogen, or timber volume, from one compartment to another. Dashed arrows represent the information transfers between compartments, for example, the relationship between nitrogen content and timber volume. Flows of nitrogen are measured in kg/ha/hr, while timber volume flows are in cu m/ha/yr and cu ft/ac/yr.[7] Driving variables are those factors which cause the model to move forward in time. In this model the driving variables are the rates of nitrogen uptake from the soil to the vegetation compartments.

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[7] 1 kg/ha = .89 lb/ac; 1 ha = 2.47 acres; 1 cu m/ha = .07 cu ft/ac.

H. Literature Review

This section presents key literature on the identification and analysis of long-term forest productivity questions. The discussion includes the nature of the management concerns and methods of analyzing the effects of management intensity on long-term productivity.

1. Introduction

There is widespread concern for the potential effects of intensive forest management on future productivity. Jorgensen, Wells and Metz (1975) studied intensive biomass production of loblolly pine (*Pinus taeda* L.) in southeastern United States. They concluded that management practices which consider the nutrient cycle may be the most economic over several rotations. Miller, Lavender and Grier (1976) discuss the nutrient cycling implications of silvicultural practices in the Douglas-fir region of the Pacific Northwest. They caution the land manager to carefully choose logging and slash treatment methods, taking special care on low quality sites which are less tolerant of nutrient losses. A summary of the impacts of harvesting methods on soils and the environment in the Pacific Northwest is given by Cromack, Swanson and Grier (1978). Road construction, timber harvesting and slash burning can contribute to soil compaction, increased organic debris in streams and accelerated nutrient losses from soil surface erosion, debris avalanches and leaching beyond the rooting zone.

As forest management practices shift toward shorter rotations and higher utilization standards, there will be an increase in nutrient losses in harvested materials, and rates of removal may exceed the natural replacement rates (Kimmins, 1977). Three aspects of nitrogen cycling which may prove critical in evaluations of a forest ecosystem's response to management are: (1) gains by nitrogen fixation; (2) mineralization of soil nitrogen; and (3) losses via denitrification (Swank and Waide, 1980).

The concern for management effects on long-term forest productivity is also evidenced by two recent symposia. The first addressed Principles of Maintaining Productivity on Prepared Sites (Tippin, 1978). The second considered the Impact of Intensive Harvesting on Forest Nutrient Cycling (State University of New York, 1979).

A second consideration is evidence which suggests that nutrient depletions are occurring in certain forested areas. The long established practice of removing the litter from Scotch pine stands (*Pinus sylvestris*) in Germany has resulted in soil nitrogen depletions and declines in growth. In the Oberpfalz region of southern Germany there are 110-year-old Scotch pine trees 6 meters in height. Research is now in progress to ameliorate the soil organic matter and nitrogen deficiencies by discontinuing the litter use and interplanting the stands with such nitrogen-fixing species as blue lupine (*Lupinus* spp.), Scotch broom (*Cytisus scoparius*) and alder (*Alnus incana* and *A. glutinosa*) (Wittich, 1954; Assmann, 1970).

In many Scandinavian forests, nitrogen has been identified as the most growth-limiting nutrient (Tamm, 1979). In North Sweden, shifts in management toward more intensive forestry are expected to increase the number of negative factors affecting long-term forest production. A decrease in forest growth reported by the latest Forest Survey of Sweden has increased the concern for long-term implications of intensive management practices (Tamm, 1979).

Second rotation Monterey pine plantations (*Pinus radiata*) in New Zealand are exhibiting nitrogen deficiencies (Stone and Will, 1965) and corresponding reductions in productivity (Whyte, 1973). Woods (1980, draft) found that slash removal caused second rotation growth declines. Webber (1978) projects nutrient depletions with intensified management of these plantations and claims that fertilization practices will be necessary to maintain productivity.

The identification of potential long-term nutrient problems is not limited to other continents. Researchers in several areas of North America have indicated the likelihood of future productivity declines with certain management prescriptions. In southeastern United States, the growth and nitrogen cycling of oak-hickory forests and loblolly pine plantations have been simulated. In both cases, substantial soil nitrogen depletions are revealed after four rotations (30 to 90 years in length) when nitrogen fertilization is not practiced (Swank and Waide, 1980; Waide and Swank, 1977). In the central Sierra Nevada region of California utilization of logging residues for fuel may increase the drain on forest fertility (Zinke, Stangenberger and Colwell, 1979). Assessments of the amount of nutrients removed in wood residues relative to the soil nutrient storage show that phosphorus removal may create a serious fertility decline on these sites.[8] Clearcutting and slashburning practices in Douglas-fir forests in coastal British Columbia may lead to major nitrogen losses from these ecosystems (Kimmins and Feller, 1976). Kimmins and Feller recommend the avoidance of slashburning on low quality sites.

Thirdly, the potential for long-term nitrogen depletion of forest soils has led to suggestions for the use of nitrogen-fixing species in the nitrogen management of forests (Cromack, Delwiche and McNabb, 1979; Haines and DeBell, 1979). My research evaluates the effect of the nitrogen-fixing species red alder (Alnus rubra) on long-term productivity. Red alder as a crop rotation with Douglas-fir is one possibility for adding nitrogen to a site (Tarrant and Trappe, 1971; Atkinson, Bormann and DeBell, 1979). Another possibility is interplanting alder with Douglas-fir (Atkinson and Hamilton, 1978). There is also current interest

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[8] P. J. Zinke, personnal communication, 1980.

in comparing the value of fertilizer and alder nitrogen additions to Douglas-fir forests (Miller and Murray, 1979).

The research cited above establishes the real possibility of long-term productivity declines from certain intensive forest management practices. There has been a progression in analytical methods to evaluate this possibility, beginning with early studies which compared nutrient gains and losses in forested watershed. A second stage was characterized by nutrient budgets of forest ecosystems. A nutrient budget represents the nutrient status of ecosystem components at one point in time. A third development was the use of nutrient budgets for forest ecosystems of several ages to represent the trends in one ecosystem over time. This was followed by the latest development of nutrient cycling simulation models. Each of these methods will be considered in turn.

2. Input-Output Nutrient Studies

Researchers at the Hubbard Brook Experimental Forest in New Hampshire used measurements of nutrient inputs and outputs to indicate whether certain nutrients were accumulating in these northern hardwood watersheds. The undisturbed forests had an annual input of 20.7 kg/ha of nitrate, ammonium and gaseous nitrogen, while the annual nitrogen output to streams was 4.0 kg/ha. This represented a net nitrogen accumulation of 16.7 kg/ha/year (Likens, Bormann, Pierce, Eaton and Johnson, 1977).

Another example of an input-output study is by Tiedemann, Helvey and Anderson (1978) in the Entiat Experimental Forest in eastern Washington. This five-year study compared the effects of wildfire and fertilization on nutrient additions and losses in four watersheds. Total nitrogen losses in streamwater increased from .27 to 3.35 kg/ha/yr the year after burning and fertilization. There was no significant difference between burned and burned/fertilized watersheds. When compared to the average nitrogen addition of 1.23 kg/ha/yr in precipitation, the result was a net loss of 2.12 hg/ha/yr.

The H. J. Andrews Experimental Ecological Reserve in western Oregon has also been the site of nutrient input-output studies (Fredriksen, 1972; Fredriksen, 1975). The undisturbed old-growth Douglas-fir forest was monitored for nitrogen additions by precipitation and dust and stream losses in solution and suspended sediment. The difference in nitrogen inputs and outputs averaged +0.51 kg/ha/yr for a two-year period (Fredriksen, 1972).

A different type of input-output study was conducted on a western larch (Larix occidentalis)/Douglas-fir ecosystem in the Coram Experimental Forest, western Montana (Stark, 1979). Various timber harvesting methods, utilization standards and slash treatments were evaluated for their effects on nitrate losses below the rooting zone, in intermittent streams and in wood and bark removed from the site. The losses were expressed relative to the additions from precipitation and the total soil nitrogen. Stark concluded that in the absence of erosion, nutrient losses from harvesting did not constitute a management problem on these sites.

As a technique for assessing effects of management intensity on long-term productivity, input-output studies have several weaknesses. First, the concentration on additions and losses precludes analysis of management effects on important internal processes, for example, mineralization of soil nitrogen and resultant nitrogen availability. Secondly, forest productivity questions address the long-term future implications of certain management practices. Yet most input-output studies are conducted over a short time period and do not reflect nutrient cycling dynamics over space or time.

3. Nutrient Budgets

The progression to budget analyses allowed the consideration of internal cycling processes. A budget is a representation of the ecosystem in terms of compartments and associated rates of nutrient transfer between compartments. A nitrogen budget for an oak-hickory forest at the Coweeta Hydrologic Laboratory in North Carolina contained 15 compartments: the aboveground vegetation, herbivores, litter, roots and mycorrhizae, microflora, soil fauna, soil organic matter and soil nitrate and ammonium nitrogen (Mitchell, Waide and Todd, 1975). Such budget analyses can reveal the relative contribution of each compartment and transfer rate to the nutrient status of the ecosystem.

Organic matter distribution and production budgets have been constructed for old-growth Douglas-fir forests in western Oregon (Grier and Logan, 1977). Nutrient budgets for these forests are reported by Sollins et al. (1980). The nitrogen budget included three compartments for nitrogen in solution and twelve additional ones representing the aboveground vegetation, nitrogen-fixing epiphytes, litter, roots and soil organic matter.

Webber's biomass and nutrient budgets of an 18-year-old Douglas-fir stand in British Columbia included the understory vegetation but not the roots (Webber, 1973). Organic matter and nutrient budgets have also been prepared for a 36-year-old Douglas-fir ecosystem at the A. E. Thompson Research Center in western Washington (Cole, Gessel and Dice, 1967; Dice, 1970). Nutrient budget comparisons have been made between 34-year-old red alder stands and old-growth and second-growth Douglas-fir (Turner, Cole and Gessel, 1976; Cole, Gessel and Turner, 1978).

A budget's ability to assess internal transfers and an ecosystem's nutrient status is an improvement over input-output studies. However, budget analyses still lack the dynamic dimensions of nutrient cycling.

4. Nutrient Budgets at Several Stand Ages

Attempts to consider nutrient cycling time dimensions have resulted in (1) budgets over some time period and (2) budgets for stands of several ages to represent trends in one stand over time. An example of the former is a ten-year study of nutrient cycling in loblolly pine plantations in North and South Carolina (Wells and Jorgensen, 1975). The second method is represented by a western Washington study of nine Douglas-fir stands that ranged in age from 9 to 95 years (Turner, 1975). Although Turner studied a mixture of plantations and naturally established stands, the budgets indicated the trend in Douglas-fir nutrient cycling with time. Heilman (1961) compiled organic matter and nitrogen budgets for five western Washington Douglas-fir stands which varied in age from 30 to 52 years (also, Heilman and Gessel, 1963).

Piecing together budgets to represent long-term productivity trends lacks consideration of the dynamic nutrient interactions. This realization has led to the development of nutrient cycling simulation models.

5. Nutrient Cycling Simulation Models

Simulation modeling as an analysis technique has several desirable characteristics. First, simulation models are designed to represent the dynamic interactions within system components. An example is the decomposition of forest floor organic matter and release of nitrogen for uptake by the vegetation. Secondly, the purpose of a simulation is to reflect dynamics over time, such as the forest stand's changing requirement for soil nitrogen. A third desirable characteristic is the ease of representing outside influences on the system. The forest management practices of timber harvesting and slash burning are two such influences. Hence, nutrient cycling simulation models are well suited to analyzing the effects of management intensity on long-term forest productivity.

The scope and structure of existing nutrient cycling simulation models varies widely. Four models in regions outside the Pacific Northwest and three within the region serve as examples. The first is a forest growth and potassium cycling simulation model of a lodgepole pine stand (<u>Pinus contorta</u>) in Colorado (Woodmansee, 1972). The purposes of the model were: (1) to study the dynamics of growth and potassium cycling, and (2) to define and quantify some of assumptions concerning clearcutting and nutrient depletions. The simulation is composed of two linked submodels for biomass and potassium. There are 23 state variables representing organic matter and potassium in the first, second, third and fourth year needles, the cones, twigs, trunks and roots, the litter and the A1 and A2 - B2 soil horizons. Woodmansee's model has a finer level of resolution than the eight-state variables in my model. The driving variable in Woodmansee's model is available photosynthate. Transfers from the photosynthate pool to the vegetation are a function of potassium availability and forest age. A value is produced for maximum potential photosynthate production with no nutrient limitations. This is then adjusted by the relative photosynthate yield, which is a function of available potassium in the soil. In contrast, my model will have a less direct link with available soil nitrogen. The driving variable of nitrogen uptake from the soil will be adjusted as nitrogen is added to the system. As soil nitrogen is depleted, my model will indicate the relative amount of this depletion and the potential implications on future forest growth. This is a less direct feedback than the one in Woodmansee's model.

The second model is a nitrogen simulation of even-aged pure loblolly pine plantations in southeastern United States (Penning de Vries, Murphy, Wells and Jorgensen, 1975). The purpose of the model was to summarize individual nitrogen cycling processes and see how they might affect the plantation's long-term productivity. The model includes sixteen state variables for organic matter and nitrogen content of first-year needles, second-year needles, branches, stem wood, stem bark, roots, mineral soil and forest floor. The limiting effect of nitrogen on growth is expressed by the relative availability of soil nitrogen. This is calculated as the amount of soil nitrogen available for uptake divided by the amount taken up in a well-stocked stand of the same age. The model by Penning de Vries _et al_., in comparison with my model, has a finer level of detail and a different relationship between nitrogen and growth.

A third model represents nitrogen cycling in an oak-hickory forest at Coweeta Hydrologic Laboratory in North Carolina (Waide and Swank, 1975, 1977; Swank and Waide, 1980). The model was constructed to address questions concerning the effect of management practices on sustainable, long-term forest productivity. The fifteen state variables consider nitrogen in the leaves, branches, stems, reproductive parts, herbivores, woody litter, O_1 litter,[9] O_2 litter, roots, mycorrhizae, soil organic matter, soil fauna, microflora and soil nitrate and ammonium nitrogen. This model has a very fine level of resolution. Waide and Swank developed indices of nitrogen cycling to analyze the relative effects of management practices on ecosystem stability. Stability comparisons between the oak-hickory forest and the loblolly plantation of Penning de Vries _et al_. (1975) required a more aggregated model of the oak-hickory system. The original fifteen nitrogen variables were aggregated into seven: leaves; branches; stems; roots; woody litter; leaf litter and soil. The aggregated model predicted less damaging management effects than predicted by the expanded model (Waide and Swank, 1977; Swank and Waide, 1980). This indicates that a model's level of resolution will influence any conclusions concerning the effects of management practices on long-term productivity.

The fourth model is one of forest floor dynamics in a northern hardwood forest at Hubbard Brook, New Hampshire (Aber, Botkin

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[9] O_1 represents litter in which the original forms of the residues can be recognized: O_2 represents the unrecognizable residues.

and Melillo, 1978, 1979). The model's purpose was to predict successional trends in forest floor conditions with various management prescriptions. Forest floor organic matter and nitrogen are represented by fourteen variables for roots in slash, wood slash, fine roots, dead woody roots, dead wood, leaves and the F and H layer.[10] The resulting measure of net nitrogen availability is calculated as the sum of mineralization from the F and H layers plus meteorological additions minus immobilization. Recent work has refined the method of predicting nitrogen mineralization (Aber and Melillo, 1980). Forest floor nitrogen cycling is linked to tree growth when projected nitrogen availability levels are input into a forest growth simulation model (Botkin, Janak and Wallis, 1972; Aber, Botkin and Melillo, 1979). Soil nitrogen availability is related to foliar nitrogen concentration, which determines relative growth rates. As multipliers in the growth model, the relative growth factors represent the effects of soil nitrogen availability on tree growth and succession.

In the Pacific Northwest there have been several approaches to nitrogen cycling simulation models of Douglas-fir forests. One considers the organic matter and nitrogen transfers in a mature Douglas-fir stand in western Washington (Riggan, 1976; Cole, Riggan, Turner, Johnson and Breuer, 1978). Sixteen state variables are used. The vegetation is represented by

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[10] The F and H layer consists of partially decomposed organic material.

nitrogen and organic matter in Douglas-fir foliage, wood and roots and in the salal understory. Douglas-fir structural nitrogen and nitrogen in enzymatic proteins are considered "fixed" nitrogen, while "mobile" nitrogen includes the free amino acids and amides. The forest floor is divided into wood, litter and humus organic matter, and wood and other organic nitrogen. The soil is represented by soil organic matter, organic nitrogen and exchangeable ammonium. This inclusion of organic matter, roots and exchangeable and mobile nitrogen, provides more detail than my model. In Riggan's work (1976), direct nitrogen feedbacks occur in several places. Nitrogen uptake by the vegetation is a function of soil exchangeable ammonium. Nitrogen incorporation and redistribution in new foliage depend on the mobile nitrogen pool. Also, biomass growth is a function of the fixed nitrogen concentration. This compares to less direct feedbacks in my model that will occur at predetermined times. While Riggan simulated 100 years of a stand's development, with or without fertilization, my model will simulate a variety of management practices, including harvesting, over several rotations (200-400 years). Riggan also used constant decomposition rates, while mine will vary with time and different management practices.

Another Pacific Northwest model simulates a seven-year-old Douglas-fir plantation in western Washington (Riggan, 1979). The model structure is similar to Riggan's mature stand model (1977), however, the young-growth simulator has a daily time resolution. This is in contrast to the yearly resolution of all previously considered models. The young-growth model was designed to simulate ten years of Douglas-fir growth, including the effect of nitrogen fertilization. The resolution and purpose of Riggan's second model (1979) were very different from the model I am constructing.

The last model considered is a comprehensive one of forest biomass production, decomposition and nutrient cycling in even-aged plantations (Kimmins and Scoullar, 1979; Kimmins, Scoullar and Feller, 1980 (draft)). The model is designed to predict long-term consequences of shifts from low to high-intensity management on: (1) biomass production; (2) ecosystem nutrient cycling; and (3) economic and energy cost benefit ratios. Management alternatives include thinning, pruning, fertilization, clearcutting, controlling brush with herbicides and varying regeneration delay. The objectives were to develop a general model applicable to different sites that would include several nutrients and use inventory type data. The overstory is represented by state variables of biomass and nutrient content in foliage, branches, bark, wood and roots. Understory biomass and nutrients are divided into shrubs, herbs and mosses. Forest floor biomass, forest floor nutrients and available soil nutrients constitute the remaining state variables. Driving variables are site specific equations of volume as a function of age. Still in the developmental stage, the model presently includes only one forest type, Douglas-fir, and one nutrient, nitrogen. The time resolution is annual and forest conditions may be simulated for 500 years.

In terms of both state variables and management alternatives, the model by Kimmins _et al_. (1980) has a much wider scope than mine. Kimmins _et al_. include a direct relationship between nitrogen availability and growth. If the demand for uptake is greater than the available soil nitrogen pool (NH_4^+ and NO_3^-), growth is reduced. When available nitrogen exceeds demand, growth is increased up to an upper limit. Provisions are also made for site quality changes over time. This treatment of nitrogen availability, growth and site quality is more detailed than mine. However, the model by Kimmins _et al_. has not yet been calibrated or validated. Therefore, its predictions are currently of a qualitative nature. Future additions include predictions of log size, valuation of management costs and benefits and an energy balance analysis (Kimmins, Scoullar and Feller, 1980 (draft)).

II. MODEL DEVELOPMENT

Discussion of the model development is divided into three sections. The first introduces the modeling strategy. The construction of the base model is described in the second section, while the third explains the addition of the management decision variables.

A. Introduction

The first consideration is the strategy for developing a model to meet the research objective. This is followed by a discussion of the main data sources and a description of the typical site assumed by the model.

1. Modeling Strategy

As mentioned in Chapter I, the scope of the research and the nature of the research questions determined the basic structure of the model (Fig. 3). The next step was identifying a strategy for building a mathematical model to represent this structure. I decided this could best be accomplished in two stages.

The first stage was the development of a base model, representing nitrogen cycling in an essentially unmanaged Douglas-fir ecosystem over a 120-year period. Using data from the literature, I developed functions for each rate of flow of nitrogen or timber volume. The combination of flow rate functions constituted the mathematical model. Next I constructed a computer simulation model to solve the mathematical model for the values of the state variables at any point in time. This first stage of model development was completed by verifying that the computer model was functioning correctly and validating the model by comparing its results with data from the literature not used in the model development.

The second stage involved the sequential addition of forest management decision variables to the base model. The decision variables were Douglas-fir rotation length, timber utilization standard, nitrogen fertilization and slash treatment. The literature was used to determine the effects of management practices on forest growth and nitrogen cycling. After the addition of each new variable, I verified the functioning of the computer model and when possible, validated the results through comparisons with the reports in the literature. This stepwise strategy to model construction proved valuable in keeping the model understandable and simple to work with at each stage in its development.

2. Data Sources

A search of the literature revealed few comprehensive studies of either nitrogen cycling in Douglas-fir ecosystems or long-term effects of management practices on nitrogen cycling. The main source of data was from Turner's sequence of nine low site

Douglas-fir stands (site class IV, 100-year basis) which ranged in age from 9 to 95 years (Turner, 1975). The stands were a mixture of plantations and naturally established stands in the A. E. Thompson Research Center in the city of Seattle's Cedar River Watershed in western Washington. Turner's study considered natural rates of nutrient cycling and the effects of nitrogen fertilizer additions.

A second data source used in model validation was Heilman's study of five Douglas-fir stands ranging from 30 to 52 years old (Heilman, 1961; Heilman and Gessel, 1963). The stands were of low site quality (site IV and V) in western Washington. Heilman determined organic matter nitrogen budgets for the five ecosystems and studied the effect of nitrogen fertilization on nitrogen cycling.

These are the two most comprehensive data sources for nitrogen cycling in second-growth Douglas-fir ecosystems in the Pacific Northwest. There are many studies which address specific processes in the cycle, such as litterfall, leaching to streams and response to clearcutting and slashburning. Using Turner's data as a base, I relied on these other studies to fill in the gaps. Whenever possible, I used data from Washington sites similar to those of Turner's. These additional data will be identified in the following sections as they contribute to the development of the model.

3. Description of the Typical Site Assumed by the Model

Most of the information on nitrogen cycling trends during a stand's development is taken from Turner (1975). Therefore, a built-in model assumption concerns the typical site being simulated. This typical site is located at the A. E. Thompson Research Center in the western foothills of the Washington Cascades at 210 meters elevation. Topography is flat to rolling. The coarse, gravelly, sandy loam soils are Everett series, mid-site class IV, developed from glacial outwash terraces. The climate is typified by an average annual precipitation of 130 cm. with a summer drought period. The Douglas-fir overstory has a density of approximately 2100 stems/ha at age 10, 2000 stems/ha at age 30, 1100 stems/ha at age 50, 1000 stems/ha at age 70 and 700 stems/ha at age 100. Principal understory species are salal (*Gaultheria shallon*), Oregon grape (*Berberis nervosa*), bracken fern (*Pteridium aquilinum*) and red huckleberry (*Vaccinium parvifolium*). For a more detailed description of the Thompson Research Center see Turner (1975) or Cole and Gessel (1968).

B. Development of the Base Model

The base model represents nitrogen cycling in an unmanaged Douglas-fir stand over 120 years of its development. The model is composed of eight state variables and eighteen flow rates, as shown in Figure 3. The state variables, Xi, represent the state of the system at any point in time and are defined in Table I. The flow rates describe flows of nitrogen, timber volume or information from one state variable to another in any given year. The symbol Fi,j will be used to represent the flow from state variable i to state variable j. F0,j represents the addition of material from outside the system to state variable j. Conversely, Fi,0 indicates a loss from state variable i out of the system. Flows of information occur when the value of one state variable is used to calculate the value of another at the same point in time. Table II defines each flow rate. The driving variables, which cause the model to move forward in time, are the rates of nitrogen uptake from the soil to the vegetation: F5,1; F5,2; and F5,3.

1. Individual Flow Rates

The individual flow rates were developed from many sources of information using a variety of techniques. When enough data were available from the literature, linear regression methods were used to develop an equation for the flow rate. If the quantity or quality of data were insufficient for regression analyses, a table of values was developed for the rate. The table contains values of the independent variable and the corresponding flow rate. For numbers between the table values, linear interpolation is used. Thus the flow rate can be shown graphically as a function of the independent variable. The tables of flow rates were often the

TABLE I. STATE VARIABLES USED IN THE MODEL

State Variable	Definition	Units
X1	Douglas-fir wood and bark nitrogen	kg/ha
X2	Douglas-fir foliage and branch nitrogen	kg/ha
X3	understory aboveground nitrogen	kg/ha
X4	forest floor nitrogen	kg/ha
X5	total soil nitrogen (to a 60cm depth)	kg/ha
X6	Douglas-fir wood and bark volume	cu ft/ha
X7	Douglas-fir foliage biomass and branch volume	kg/ha cu ft/ha
X8	nitrogen in total aboveground vegetation; X8=X1+X2+X3	kg/ha

TABLE II. RATES OF FLOW OF NITROGEN, TIMBER VOLUME OR INFORMATION USED IN THE MODEL.

Flow	Definition	Units
F0,4	Rate of nitrogen input to the forest floor from precipitation, nitrogen fixation and fertilization	kg/ha/yr
F0,5	Rate of nitrogen input to the soil from nitrogen fixation	kg/ha/yr
F1,0	Rate of loss of nitrogen from Douglas-fir wood and bark out of the system due to harvesting	kg/ha/yr
F1,4	Rate of flow of nitrogen from the Douglas-fir wood and bark to the forest floor (wood and bark litterfall)	kg/ha/yr
F2,0	Rate of loss of nitrogen from Douglas-fir foliage and branches out of the system due to harvesting	kg/ha/yr
F2,4	Rate of flow of nitrogen from Douglas-fir foliage and branches to the forest floor (foliage and branch litterfall)	kg/ha/yr
F3,0	Rate of loss of nitrogen from the aboveground understory vegetation out of the system due to harvesting and slash treatment	kg/ha/yr
F3,4	Rate of flow of nitrogen from the aboveground understory vegetation to the forest floor (understory litterfall)	kg/ha/yr
F4,0	Rate of loss of nitrogen from the forest floor out of the system due to volatilization and litter removal	kg/ha/yr
F4,5	Rate of flow of nitrogen from the forest floor to the soil	kg/ha/yr
F5,0	Rate of nitrogen losses from the soil out of the system (sum of erosion, denitrification and leaching beyond the rooting zone)	kg/ha/yr
F5,1	Rate of flow of nitrogen from the soil to the Douglas-fir wood and bark	kg/ha/yr
F5,2	Rate of flow of nitrogen from the soil to the Douglas-fir foliage and branches	kg/ha/yr

TABLE II. (CONT.)

F5,3	Rate of flow of nitrogen from the soil to the aboveground understory vegetation	kg/ha/yr
F6,0	Rate of flow of Douglas-fir wood and bark volume out of the system due to harvesting	m^3/ha/yr
F7,0	Rate of flow of Douglas-fir branch volume out of the system due to harvesting	m^3/ha/yr
F1,6	Rate of flow of information from Douglas-fir wood and bark nitrogen to wood and bark volume	m^3/ha/yr
F2,7	Rate of flow of information from Douglas-fir foliage and branch nitrogen to foliage biomass and branch volume	kg/ha/yr m^3/ha/yr

result of a number of successive simulations, combined with the best available knowledge in that field. In certain cases, where there were little or no data, current scientific opinions formed the basis for assumptions of rate values.

Each flow rate is now considered in detail. Intermediate functions, designated Gi, simplify the model and are introduced and defined as needed. Table III summarizes the intermediate functions.

F0,4

The rate of nitrogen input to the forest floor is represented by:

$F0,4 = G8 + G9 + G14$

where G8 = net rate of nitrogen input from precipitation (including throughfall and stemflow for both the overstory and understory vegetation);

G9 = rate of input from nitrogen fixation; and

G14 = rate of nitrogen input from fertilization.

Assuming no major climatic changes, the nitrogen in precipitation alone is relatively constant over time on a given site. The enrichment of the precipitation as it passes through the forest canopy or down the stems will vary with the amount and nitrogen content of the vegetation present. At the Thompson Research Center, Cole, Gessel and Dice (1967) measured 1.1 kg/ha/yr nitrogen in precipitation alone. This implies that the minimum amount of

TABLE III. INTERMEDIATE FUNCTIONS USED IN THE MODEL.

Function	Definition
G1	Rate of nitrogen loss from the forest floor by volatilization to the atmosphere.
G2	Rate of nitrogen loss from the forest floor by litter removal after timber harvesting.
G3	Rate of soil nitrogen loss by physical erosion processes.
G4	Rate of soil nitrogen loss by denitrification.
G5	Rate of soil nitrogen loss in solution through leaching beyond the rooting zone.
G6	Table of the nitrogen uptake rate from the soil to the understory vegetation; table values are in three-year increments.
G7	Table of the litterfall rate from the understory nitrogen to the forest floor; table values are in three-year increments.
G8	Net rate of nitrogen input to the forest floor from precipitation.
G9	Rate of nitrogen input to the forest floor from nitrogen fixation.
G10	Table of the litterfall rate from Douglas-fir foliage and branch nitrogen to the forest floor; table values are in two-year increments.
G11	Table of the nitrogen uptake rate from the soil to the Douglas-fir foliage and branches; table values are in two-year increments.

TABLE III. (CONT.)

G12	Table of the rate of litterfall from the Douglas-fir wood and bark nitrogen to the forest floor; table values are in 20-year increments.
G13	Table of the rate of nitrogen transferred from the forest floor to the soil; table values are in three-year increments.
G14	Rate of nitrogen input to the forest floor from urea fertilization.

nitrogen added to the site annually is 1.1 kg/ha. Turner (1975) estimated additions of nitrogen from both overstory and understory throughfall and stemflow, ranging from 1.9 to 5.4 kg/ha/yr. Using linear regression techniques, Turner's data and the constraint of a minimum input of 1.1 kg/ha/yr, I developed the following function for G8:

$$G8 = 1.1 + \frac{X8}{91.3 + .07(X8)}$$

where X8 is the nitrogen in the total aboveground vegetation. This function does not require an upper bound, since experimentation with the model revealed that X8 would never exceed 700 kg/ha/yr. Figure 4 shows both Turner's data and the regression function for the net precipitation input to the forest floor.

The second component of F0,4 is the input from nitrogen fixation. Free-living bacteria in the forest floor of Douglas-fir stands have the ability to fix atmospheric nitrogen (Larsen and Harvey, 1978). An estimated 5 kg/ha/yr of nitrogen is fixed in down logs in old-growth Douglas-fir forests in the western Oregon Cascades (Cromack, Swanson and Grier, 1978). However, quantitative data are still lacking for second-growth stands. I assumed a forest floor nitrogen fixation input of 1.0 kg/ha/yr.[11] Therefore, G9 = 1.0.

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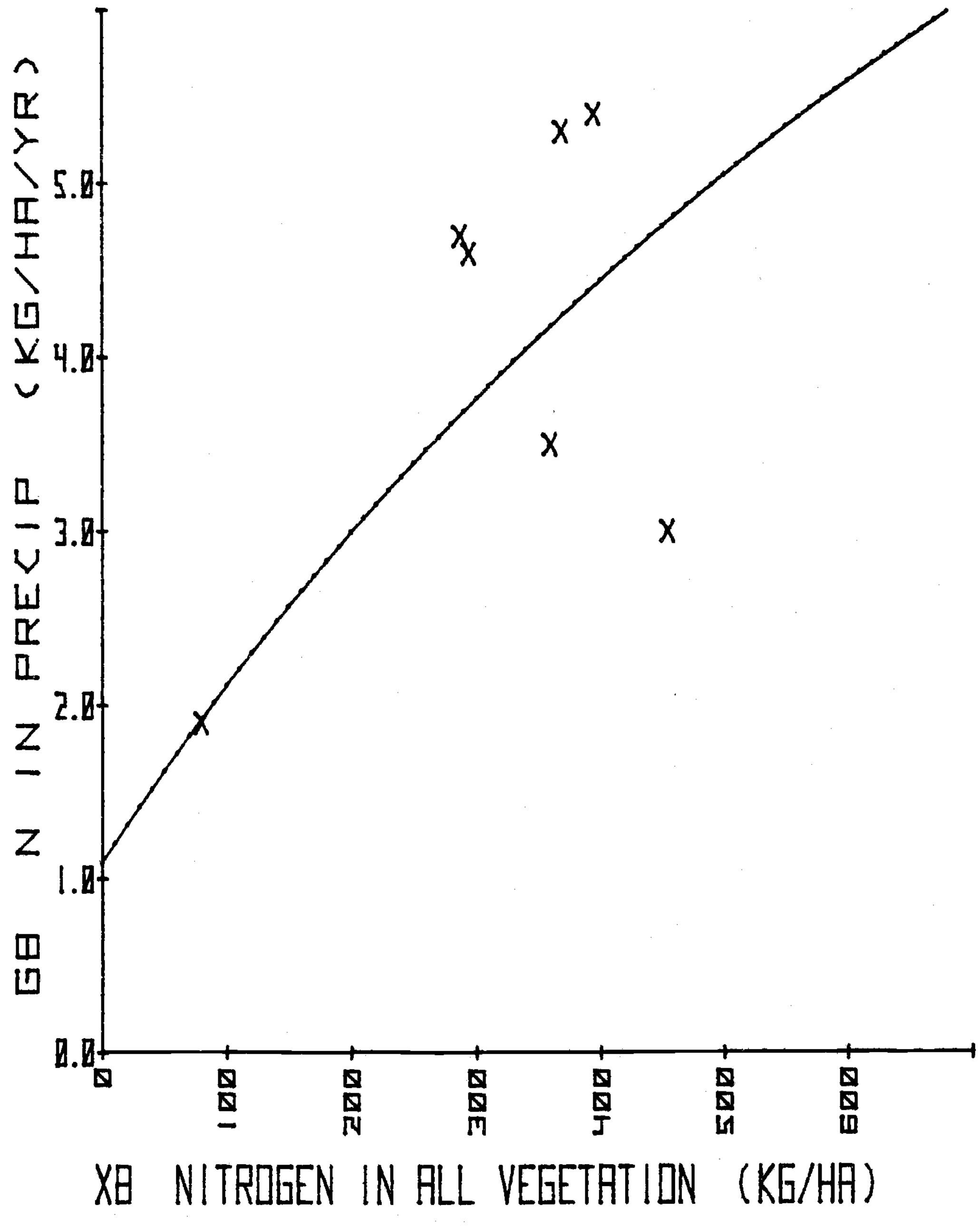
[11] Based on personal communications with W. Sylvester and K. Cromack, Jr., 1980.

FIGURE 4. Rate of nitrogen addition to the forest floor in precipitation, throughfall and stemflow (G8) (X = data from Turner (1975); ___ = rate used in the simulation).



The last component of F0,4 is the nitrogen input rate to the forest floor from fertilization (G14). In the base model G14 = 0.0.

F0,5

The rate of nitrogen input to the soil from biological fixation is zero in the base model. This rate will change when a red alder rotation occurs.

F1,0

F1,0 is the rate of removal of nitrogen from the site in Douglas-fir wood and bark. This rate is due to timber harvesting and is zero in the base model.

F1,4

The rate of flow of nitrogen from the Douglas-fir wood and bark to the forest floor is the wood and bark litterfall rate, represented by F1,4. Turner (1975) presented data on the amount of nitrogen in wood and bark litterfall, but not on its frequency of occurrence over time. Since a tree will often be standing dead for a number of years before it falls to the forest floor, stand mortality data are not particularly useful in estimating wood and bark litterfall occurrence. Therefore, I decided to use a probability distribution to represent the occurrence of wood and bark litterfall as a function of stand age. Of the nine stands studied by Turner, evidence of wood and bark litterfall was found in only three, aged 42, 49 and 73 years. I assumed that as the age of the stand increases, the probability of wood and bark litterfall occurring also increases.

Next, I developed a table to represent the nitrogen in wood and bark litterfall as a function of stand age. I assumed that as the stand gets older, the size of the material added by wood and bark litterfall increases, resulting in an increase in the amount of nitrogen added by the litterfall. This assumption, combined with Turner's data, resulted in Table IV, the amount of nitrogen in wood and bark litterfall. Linear interpolation is used for ages that fall between table values, as shown in Figure 5.

The following process was then used to estimate the occurrence of wood and bark litterfall. In the base model, the accumulation of nitrogen in the wood and bark is the net difference between additions through uptake and losses by litterfall. This can be represented by:

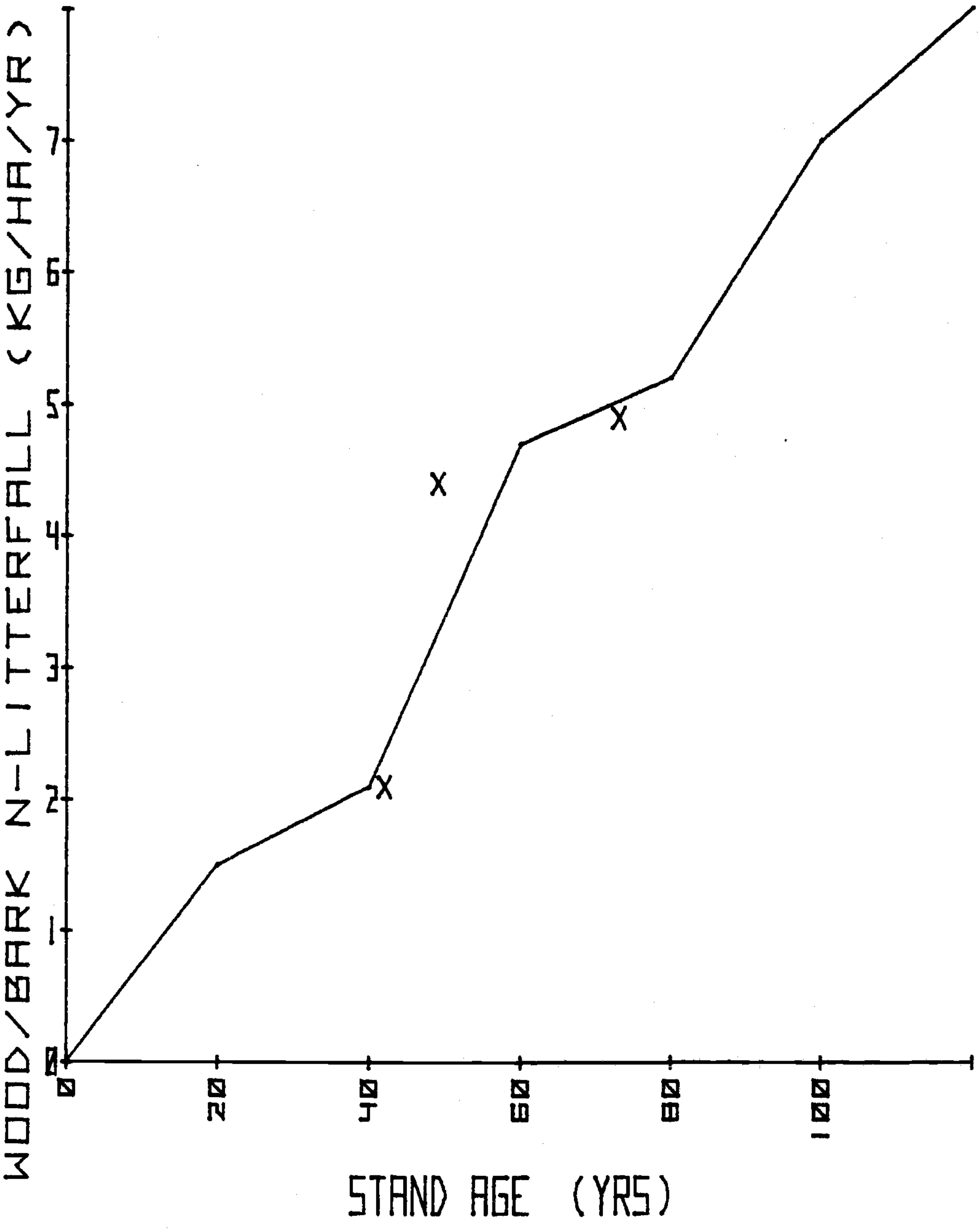
$$N_w(t) = N_w(t-1) + \text{uptake rate} - \text{litterfall rate}$$

where $N_w(t)$ is the accumulation of nitrogen in the wood and bark at time t. Turner measured the accumulation of nitrogen in the wood and bark over time and estimated the rate of nitrogen uptake from the soil. This leaves the litterfall rate as the only unknown. Since wood and bark litterfall is discontinuous over time, it is best represented by a discrete probability distribution.

TABLE IV. AMOUNT OF NITROGEN IN WOOD AND BARK LITTERFALL USED IN THE MODEL.

stand age (yrs.)	nitrogen in stem litterfall (kg/ha)
0	0.0
20	1.5
40	2.1
60	4.7
80	5.2
100	7.0
120	8.0

FIGURE 5. Nitrogen transferred to the forest floor by wood and bark litterfall (F1,4) (X = data from Turner (1975); ____ = transfer rate used in the simulation).



Therefore, I chose initial values for the relative probability of litterfall occurring in each 20-year-age class: 0-20 years, 21-40 years, etc. The sum of the relative probabilities gives the cumulative distribution. Then, by generating a uniformly distributed random number between zero and one, I sample from the cumulative probability distribution function and determine whether or not wood and bark litterfall occurs in a given year. When it does occur, the amount of nitrogen transferred to the forest floor is determined by the values in Table IV. Using these initial probability estimates, Turner's uptake estimates and the amount of nitrogen in wood and bark litterfall (Table IV), I simulated the accumulation of nitrogen in the wood and bark. I then compared the simulated accumulation with Turner's data on nitrogen accumulation over time, and adjusted the initial probability estimates accordingly. Through this iterative process I arrived at the following probabilities for the occurrence of wood and bark litterfall:

Stand age (yrs.)	relative probability of wood and bark litterfall occurring	cumulative probability
0 - 20	.10	.10
21 - 40	.15	.25
41 - 60	.17	.42
61 - 80	.18	.60
81 - 100	.20	.80
101 - 120	.20	1.00

The use of the above probability table, in combination with a random number and Table IV, determines the occurrence and amount of wood and bark nitrogen litterfall.

F2,0

The rate of nitrogen removal from the Douglas-fir foliage and branches due to harvesting is indicated by F2,0. In the base model, this rate is zero.

F2,4

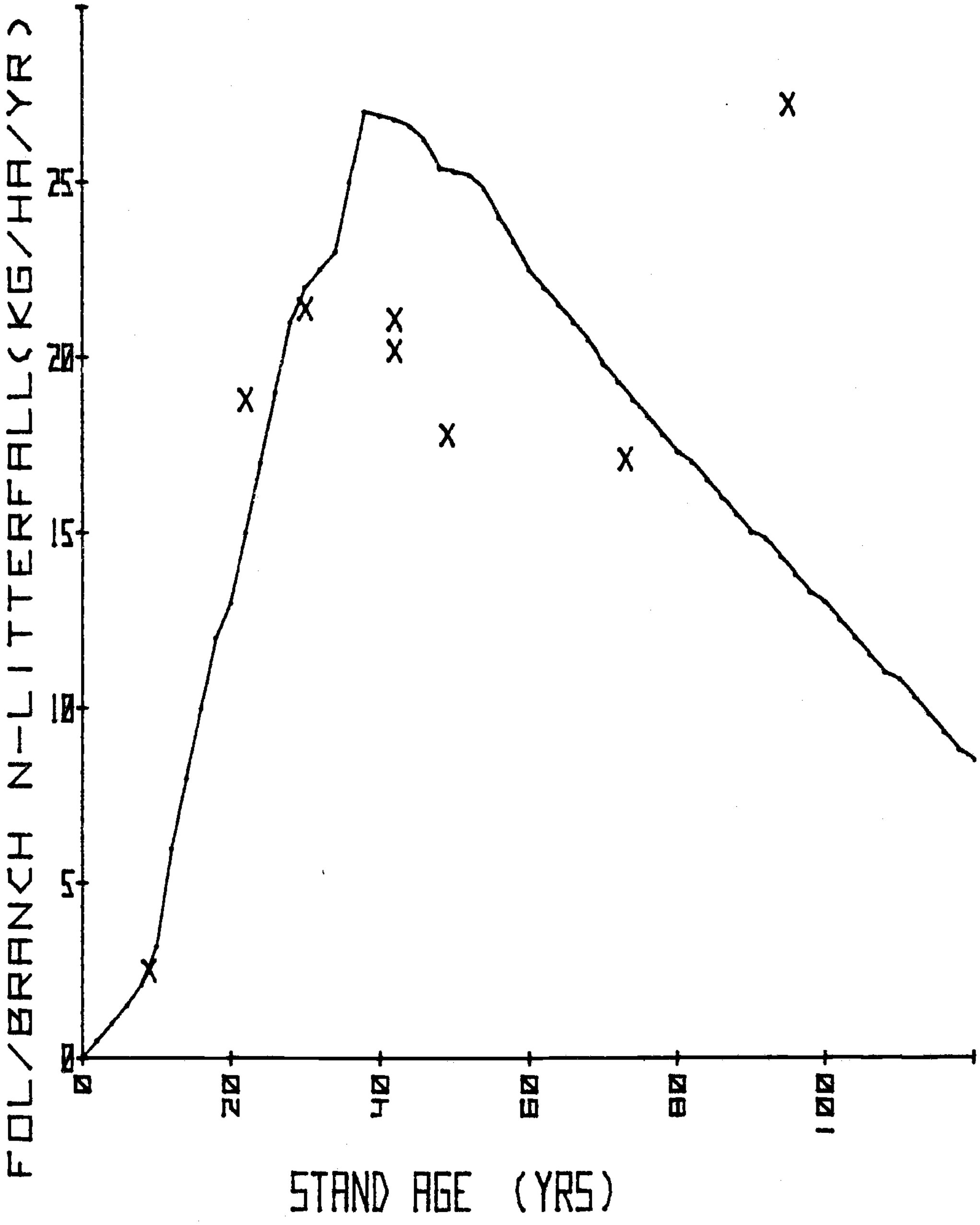
F2,4 represents the rate of flow of nitrogen from the Douglas-fir foliage and branches to the forest floor. The development of this rate was similar to the method used in F1,4. The accumulation of nitrogen in the foliage and branches is equal to the net difference between additions through uptake and losses by foliage and branch litterfall. This is represented by:

$$N_f(t) = N_f(t-1) + \text{uptake rate} - \text{litterfall rate}$$

where, $N_f(t)$ is the accumulation of nitrogen in the foliage and branches at time t. Turner's data included estimates of all three processes: litterfall, uptake and accumulation. Figure 6 shows the litterfall data plotted as a function of stage age.

Attempts to use the results of a regression analysis of Turner's litterfall data were unsuccessful. The regression equation predicted a leveling off of litterfall rates with increasing stand age. This resulted in a rapid decline in simulated foliage

FIGURE 6. Rate of nitrogen transfer to the forest floor by Douglas-fir foliage and branch litterfall (F2,4) (X = data from Turner (1975); ___ rate used in the simulation).



and branch nitrogen accumulation with time. However, Turner's own measurements of accumulation showed a characteristics "S" shaped curve with accumulation stabilizing, not declining, with time. Therefore, I assumed a decreasing trend in litterfall rates at the higher ages. This is an ecologically consistent assumption, since the litterfall rate should have a trend similar to the growth rate. I then selected initial values for a table of foliage and branch litterfall as a function of stand age. The table is represented by the intermediate function G10. Through adjustments in the table values over successive simulations, I arrived at the rate of foliage and branch litterfall shown in Figure 6.

F3,0

The rate of removal of nitrogen from the site in understory aboveground vegetation is indicated by F3,0. In the base model, this rate is zero.

F3,4

F3,4 symbolizes the rate of flow of nitrogen from the understory vegetation to the forest floor. Several regression equations were fitted to Turner's understory litterfall data, but the regressions produced unrealistic trends in simulated understory nitrogen accumulation. This led to use of the same iterative procedure as in the other two litterfall flows (F2,4 and F1,4). I developed an initial table of understory litterfall rates as a function of stand age. These rates were then adjusted until the simulated nitrogen accumulation over time reflected Turner's accumulation values. The intermediate function G7 represents the tabled values. The resultant understory nitrogen litterfall rate is indicated in Figure 7.

F4,0

The rate of flow of nitrogen from the forest floor out of the system is represented by:

$$F4,0 = G1 + G2$$

where G1 = rate of loss by volatilization to the atmosphere; and

G2 = rate of loss by litter removal after harvesting.

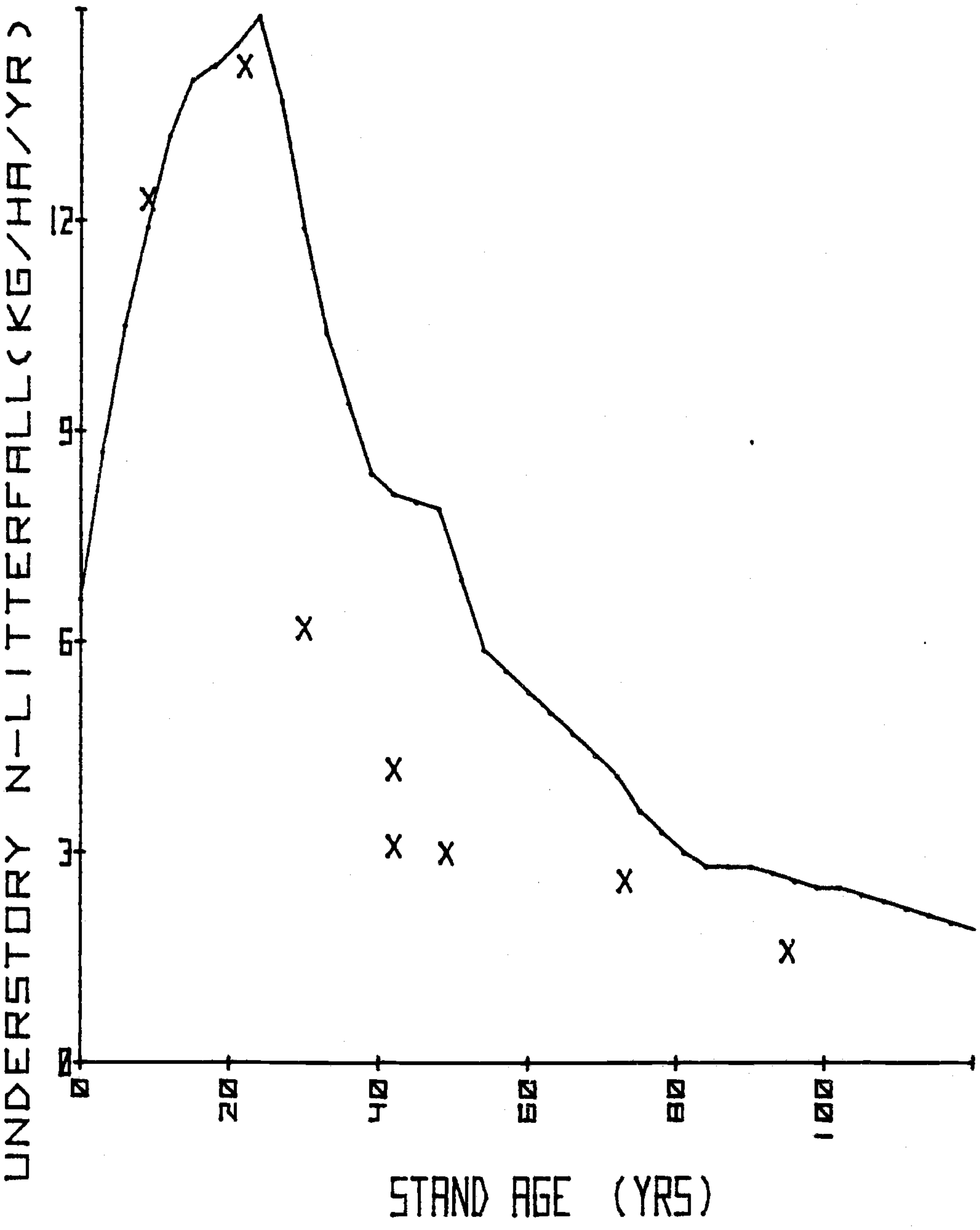
I assumed that the natural ammonia volatilization loss is zero in an unfertilized, unburned forest (G1 = 0.0). This assumption is consistent with Keeney's opinion that ammonia volatilization is probably insignificant in unfertilized forests (Keeney, 1980).

In the base model, the rate of loss of nitrogen in the forest floor due to litter removal is not used. Therefore, G2 is zero.

F4,5

The rate of flow of nitrogen from the forest floor to the soil, F4,5, has two components. The first is the direct nitrogen addition from decomposition of forest floor materials. This addition

FIGURE 7. Rate of nitrogen transfer from the understory vegetation to the forest floor (F3,4) (X = data from Turner (1975); ___ = rate used in the simulation).



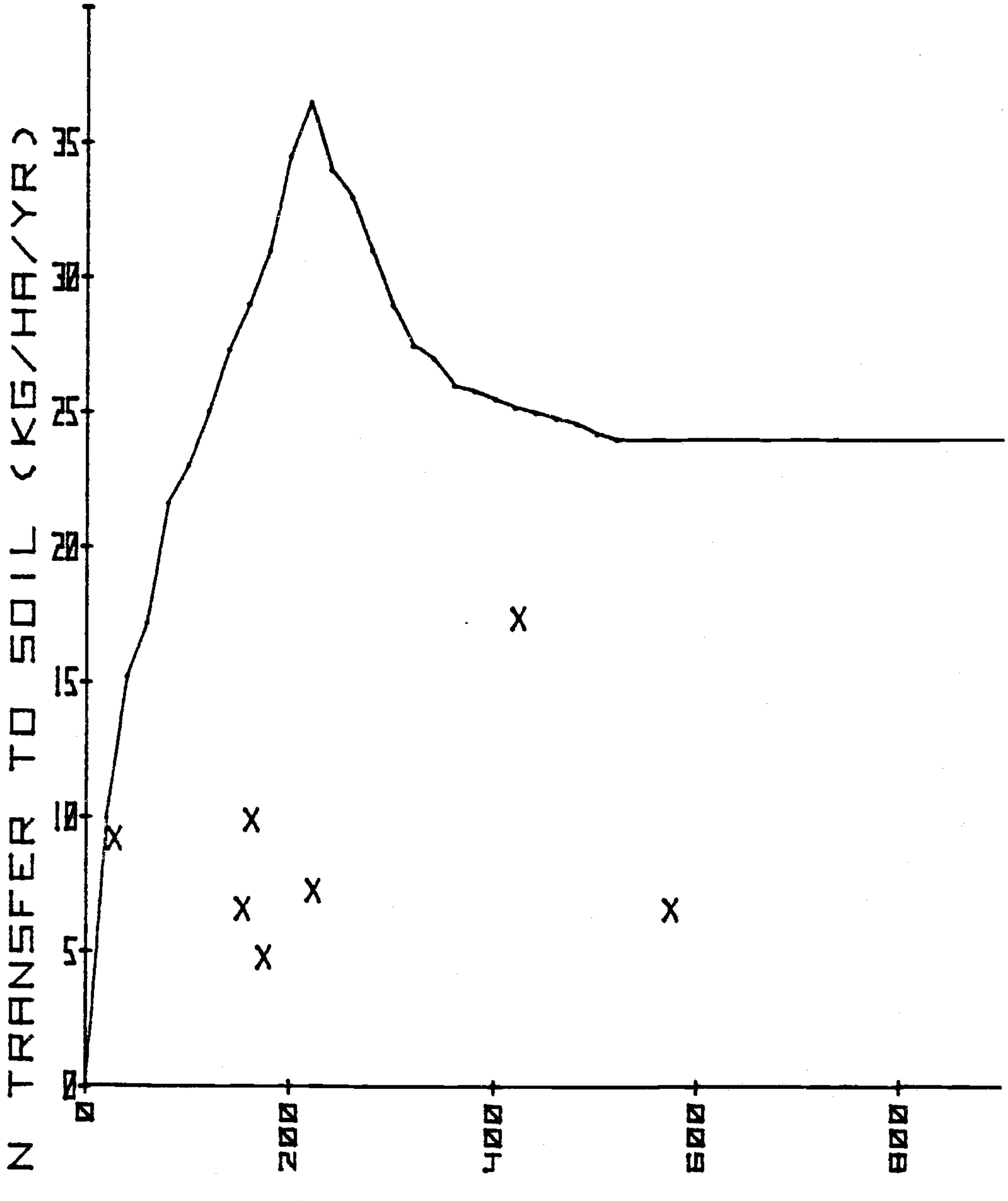
may be from nitrogen in organic matter or in solution. The second component indirectly reflects nitrogen uptake from the forest floor. A portion of the yearly uptake by the vegetation comes from the forest floor solution. F4,5 represents that portion by an indirect flow from the forest floor through the soil to the vegetation. This representation of forest floor uptake is for model simplification purposes, due to the difficulty of estimating the proportion taken up from the forest floor by each vegetation compartment.

In the model, F4,5 is represented as a function of the total forest floor nitrogen (X4). Turner (1975) estimated values ranging from 4.8 to 17.4 kg/ha/yr for the solution flow from the forest floor to the soil (see Fig. 8). Cole and Gessel (1965) found an average forest floor to soil solution transfer of 4.7 kg/ha/yr in a 32-year-old Douglas-fir stand. In both of these studies the data are for solution transfers only. Not included in these measurements are the forest floor uptake component and any physical incorporation of organic matter into the soil.

Therefore, I developed a table of values for F4,5, based on Turner's forest floor nitrogen accumulation data and on the previously developed rates of nitrogen input to the forest floor in litterfall (F1,4 + F2,4 + F3,4). The table is represented by the intermediate function G13. Using the relationship:

$$N_{ff}(t) = N_{ff}(t-1) + (F1,4 + F2,4 + F3,4) - F4,5$$

FIGURE 8. Rate of nitrogen transfer from the forest floor to the soil (F4,5) (X = data from Turner (1975); ___ = rate used in the simulation).



where $N_{ff}(t)$ is the amount of nitrogen accumulated in the forest floor at time t, I estimated values for the transfer of nitrogen from the forest floor to the soil, as shown in Figure 8.

F5,0

The rate of flow of soil nitrogen out of the system is represented by:

$$F5,0 = G3 + G4 + G5$$

where G3 = rate of loss by physical erosion processes;
G4 = rate of loss by denitrification;
G5 = rate of solution loss through leaching beyond the rooting zone.

The first component, the physical loss of soil nitrogen, is difficult to estimate. Soil can be lost from the site by a range of processes, including surface erosion, root throw, soil creep, soil slumps, debris avalanches and earth flows. Turner (1975) assumed that there was no erosional loss for the soils in the Thompson Research Center. Mersereau and Dyrness (1972), in a study on Watershed 1 of the H. J. Andrews Forest in western Oregon, assumed no measurable soil movement on their control plots. Another study in the H. J. Andrews, on Watershed 10, indicated a loss of .16 kg/ha/yr organic nitrogen in sediments in streams (Fredriksen, 1971). Swanson[12] estimated a nitrogen loss

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[12] F. J. Swanson, U.S.F.S., Forest Science Lab., Corvallis, OR. 1980 unpublished data on Watershed 10, H. J. Andrews Forest, OR.

of .008 kg/ha/yr in soil surface erosion on Watershed 10. For this same watershed, an estimated 70 kg/ha organic matter was lost annually as a result of the combined processes of surface erosion, creep, root throw, debris avalanches, slumps and earthflows (Swanson, Fredriksen and McCorison, 1980 (in press)). Assuming an average nitrogen content of .36% for the organic material,[13] the result is a nitrogen loss of 0.252 kg/ha/yr.

The model assumes the rate of nitrogen lost by physical erosion processes is 0.25 kg/ha/yr (G3 = 0.25). This assumption is based on Swanson's Watershed 10 data. Although the soils in Watershed 10 differ from those of Turner's Washington sites, Swanson's is the best available information on the overall nitrogen loss from the various erosion processes.

The second component of F5,0 is the rate of soil nitrogen lost by denitrification. There are presently no date on denitrification losses in Pacific Northwest forests. The relatively small proportion of nitrate in these soils (Johnson, 1979) has led to the opinion that denitrification occurs at low, possibly insignificant levels. Therefore, I assumed a denitrification loss of 1.0 kg/ha/yr.

The last component is the loss of nitrogen in solution by leaching through the soil below the rooting zone. Turner's estimates (1975) for this loss ranged from 1.9 to 4.0 kg/ha/yr, with an average of 3.1 kg/ha/yr. On a similar site, Cole and Gessel (1965) reported 0.65 kg/ha/yr of nitrogen lost in solution. Second-growth Douglas-fir stands in British Columbia averaged losses of

0.60 kg/ha/yr (Kimmins and Feller, 1976), while in western Oregon old-growth stands the rate was 0.08 kg/ha/yr (Fredriksen, 1971). This constitutes a wide range of estimates for solution losses of nitrogen. The model assumes this loss is a constant 3.1 kg/ha/yr, based on Turner's data. Although Turner's estimates are higher than the others, they were chosen to represent the most conservative rate for possible solution losses from the system. Due to the lack of data on potential variations with stand age, the rate is represented as a constant over time. Therefore, G5 = 3.1.

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[13] Ibid.

F5,1

F5,1 represents the rate of nitrogen uptake from the soil to the Douglas-fir wood and bark. A general trend shows increasing uptake during a stand's early years, peaking at about the time of maximum crown development (ages 30-40) and then declining in the later years (Cole, Riggan, Turner, Johnson and Breuer, 1978. As shown in Figure 9, Turner's (1975) wood and bark uptake data are not very useful for indicating the form of the relationship between uptake and stand age. However, the general trend established by Cole et al. makes it possible to select a functional form (for example, $Y = aX^b c^X$) and use Turner's data to scale the function into a realistic range. Using this procedure, the following function was developed for the rate of nitrogen uptake from the soil to the wood and bark:

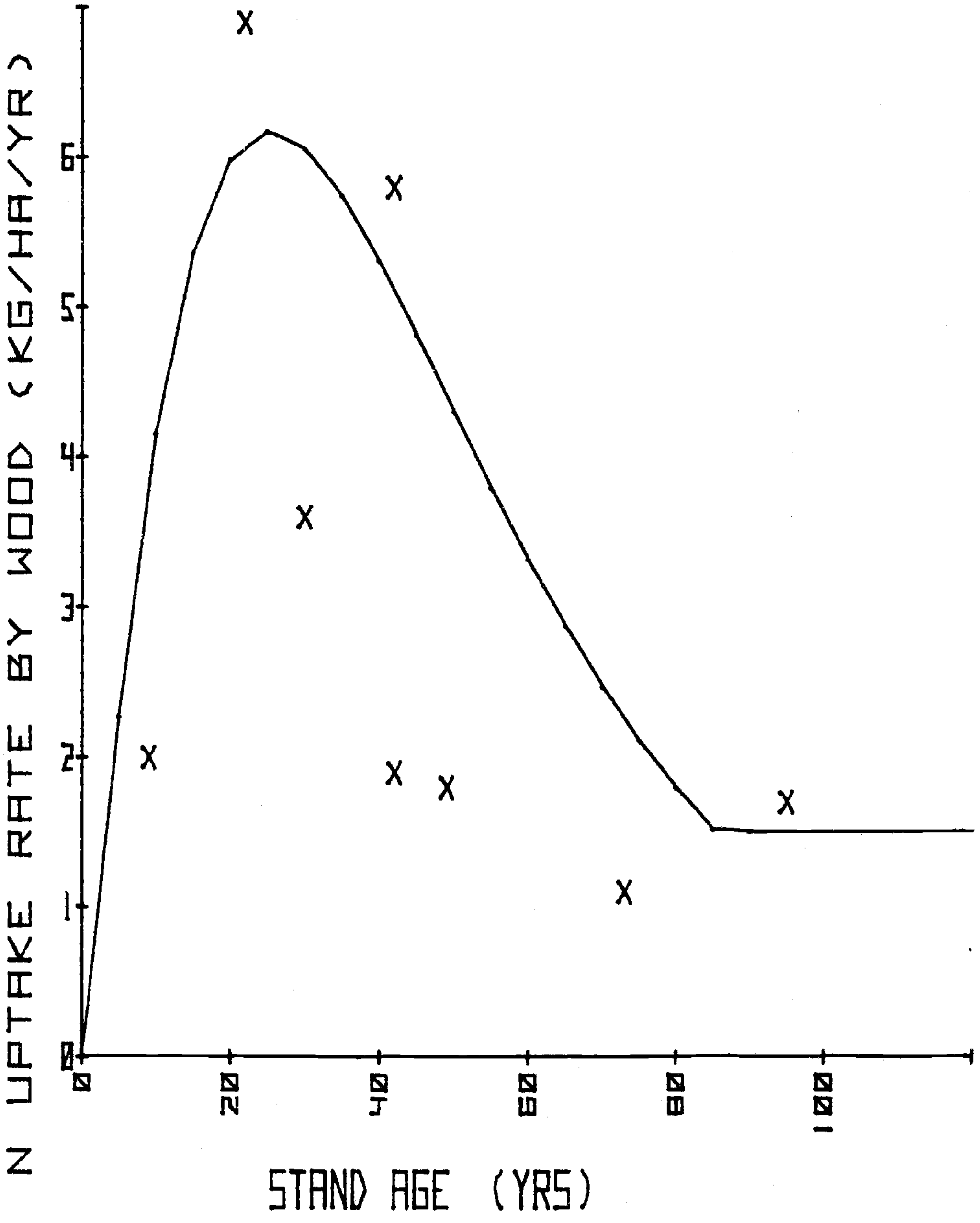
$$F5,1 = .4051\ (AGE^{1.2207})(.9529^{AGE}) \quad \text{if } 0 \leq AGE \leq 85$$

where AGE is stand age. This equation exhibits the generally established trend in uptake rates. But when stand age is greater than 85 years, the uptake rate declines to ecologically unrealistic levels. It is more realistic to expect nitrogen uptake rates to stabilize in older stands. Therefore, when stand age is greater than 85 years, the uptake rate is set at a constant 1.5 kg/ha/yr:

$$F5,1 = 1.5 \qquad \text{if } AGE > 85$$

Figure 9 shows the rate of nitrogen uptake from the soil to the

FIGURE 9. Nitrogen uptake rate from the soil to the Douglas-fir wood and bark (F5,1) (X = data from Turner (1975); ___ = rate used in the simulation).



wood and bark.

F5,2

F5,2 represents the nitrogen uptake from the soil to the Douglas-fir foliage and branches. Turner's foliage and branch uptake data are presented in Figure 10. Based on these data and the general nitrogen uptake trend described in the previous section (F5,1), a table was developed for uptake rates as a function of stand age. The table is represented by the intermediate function G11. A graph of the foliage and branch uptake rate is shown in Figure 10.

F5,3

The rate of nitrogen uptake from the soil to the understory vegetation is represented by F5,3. Development of this rate followed the same procedure as in F5,2. The intermediate function G6 represents the table of understory uptake rates as a function of stand age. Figure 11 shows both Turner's data and a graph of the rate of nitrogen uptake by the understory vegetation.

F6,0

F6,0 is the rate of removal of Douglas-fir wood and bark volume from the site. This rate is initiated by timber harvesting and therefore is zero in the base model.

FIGURE 10. Nitrogen uptake rate from the soil to the Douglas-fir foliage and branches (F5,2) (X = data from Turner (1975); ___ = rate used in the simulation).

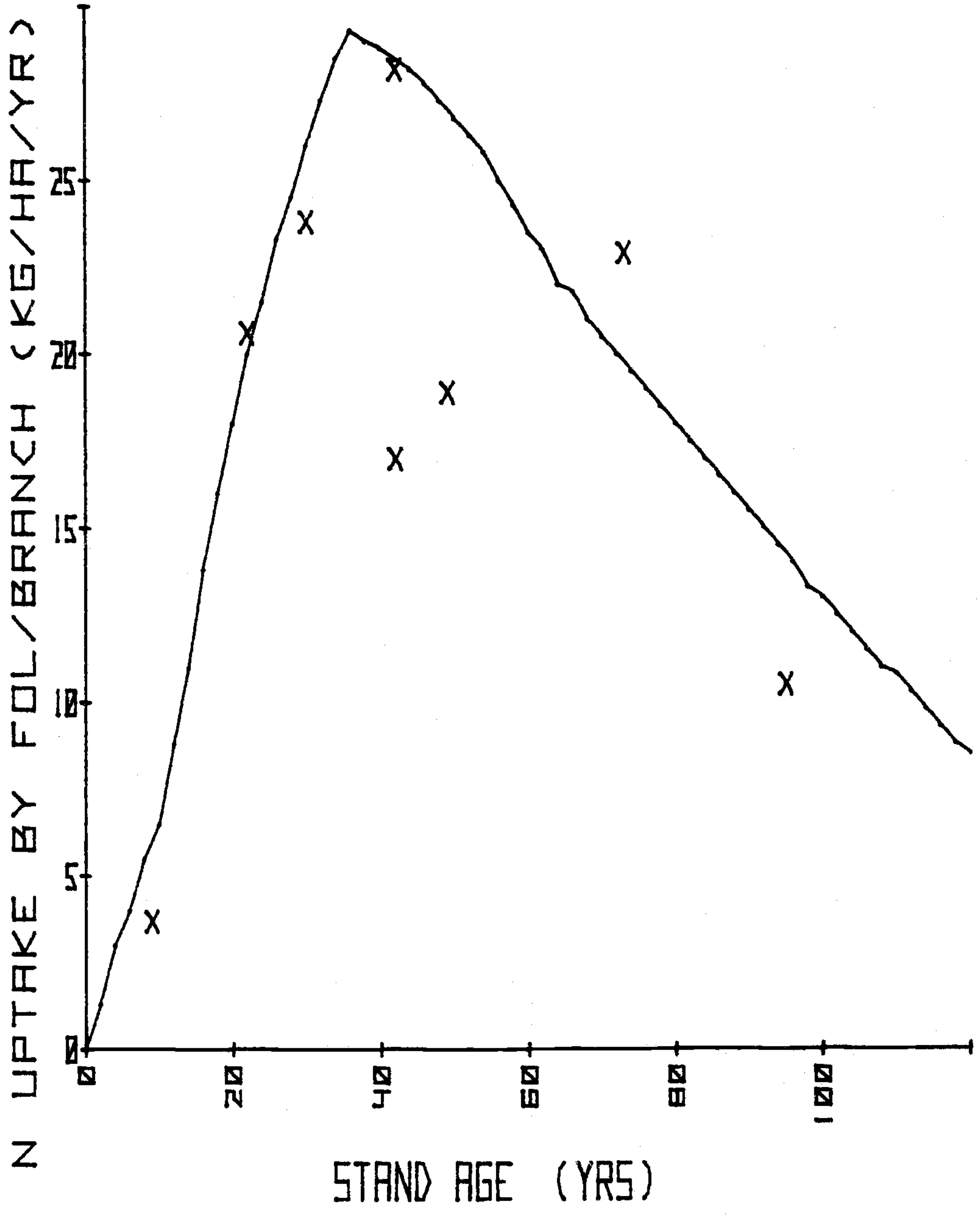
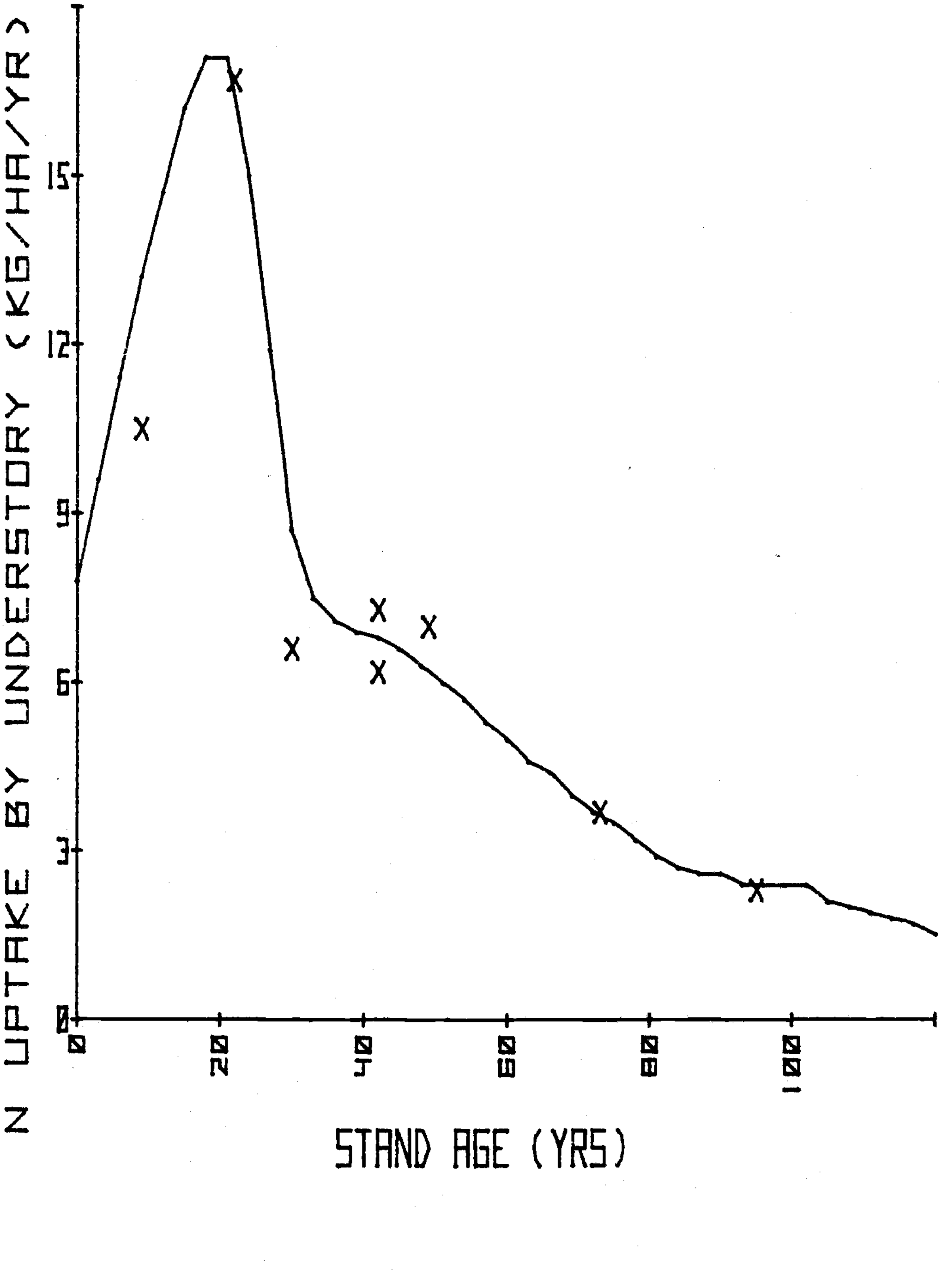


FIGURE 11. Rate of nitrogen uptake from the soil to the understory vegetation (F5,3) (X = data from Turner (1975); ___ = rate used in the simulation).



F7,0

The rate of removal of Douglas-fir branch volume from the site is represented by F7,0. In the base model this rate is zero.

F1,6

F1,6 represents the information flow from Douglas-fir wood and bark nitrogen to wood and bark volume. The conversion from nitrogen to volume occurs in two steps.

The first was accomplished through the development of a regression of wood and bark biomass as a function of nitrogen, based on data from Turner (1975). The following straight line regression through the origin represents this relationship:

$$B_w = 1095.31\ (N_w) \qquad R^2 = .85^{14}$$

where B_w is wood and bark biomass in kg/ha and N_w is wood and bark nitrogen in kg/ha. Figure 12 shows both the regression and Turner's data.

Underlying this straight line regression is the assumption that the nitrogen concentration remains constant throughout the range of biomass values, and hence, constant over stand age. This assumption may be questionable based on cases of possible increases in foliar nitrogen concentration with increasing age of Monterey pine in Australia and New Zealand (Turner, Dice, Cole and Gessel, 1978,

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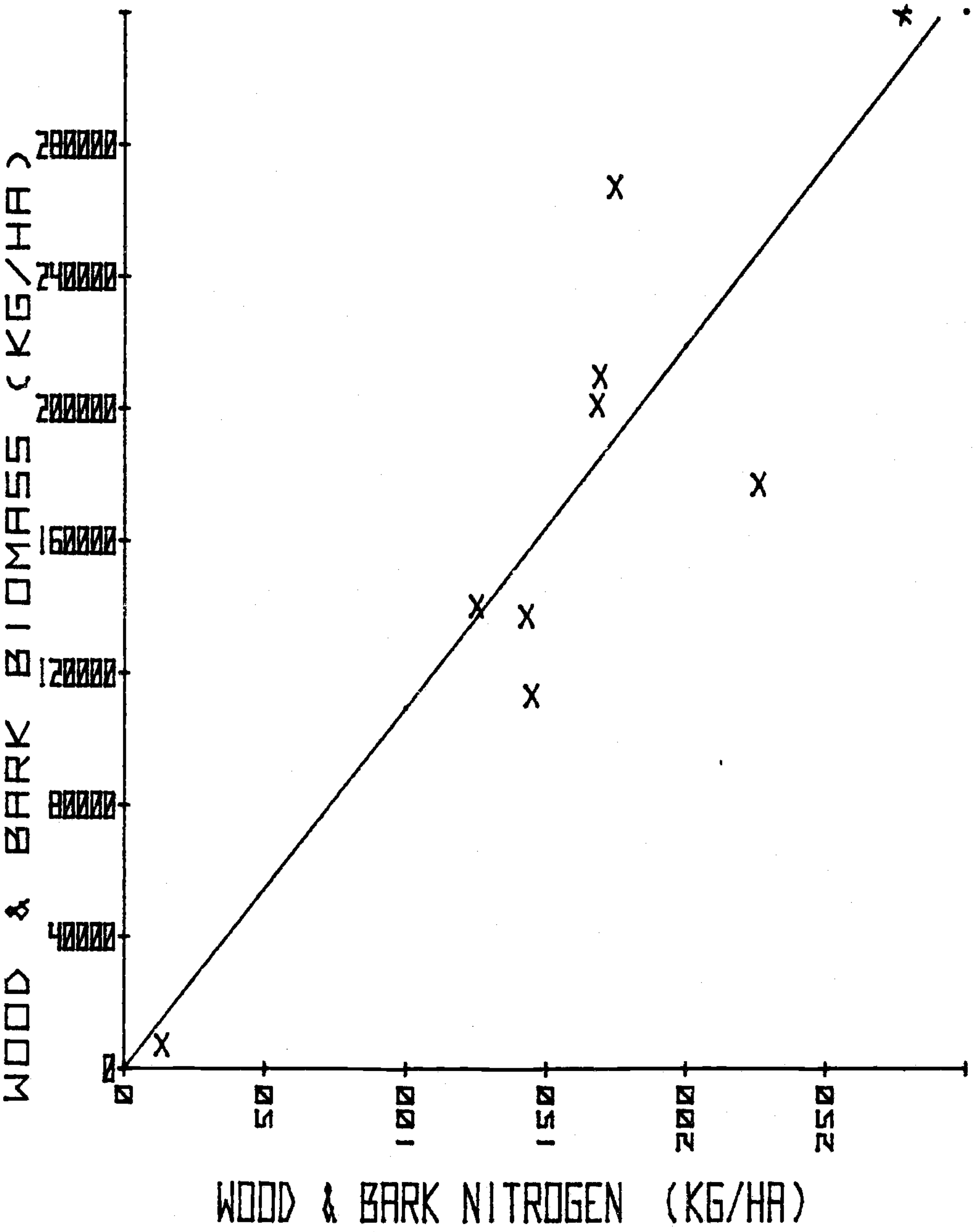
[14] Coefficient of determination.

FIGURE 12. Wood and bark biomass as a function of wood and bark nitrogen (X = data from Turner (1975); ___ = relationship used in the simulation).



p. 7). However, the same review finds decreasing foliar nitrogen concentrations with increasing age in Agathis australis, and no change in concentration with age in Scotch pine in Germany or Monterey pine in New South Wales. The authors conclude that tree age does affect the concentration of nitrogen in foliage, but this is probably a reflection of changes in the availability of soil nitrogen as the stand ages. The validity of the assumption of constant nitrogen concentration over age is supported in Douglas-fir by an examination of Turner's (1975) and Heilman's (1961, p. 125) age sequences of stands. Therefore, the use of a straight line regression seems reasonable for the site being simulated.

The second step entails the following conversion from biomass to volume, using the specific gravity (s.g.) of wood and bark.

$$\text{volume } \frac{m^3}{ha} = \frac{\text{biomass } \frac{kg}{ha}}{\text{s.g. } \frac{g}{cm^3}} \times \frac{1000g}{kg} \times \frac{1m^3}{1{,}000{,}000 \text{ cm}}$$

$$\text{volume } \frac{m^3}{ha} = \frac{\text{biomass}}{\text{s.g.}} \times .001 \qquad \text{where s.g.} = .45 \text{ g/cm}^3$$

The above volume conversion assumes that the specific gravity does not change with the age (or size) of the tree. McKimmy (1966) showed a variation in specific gravity with age, ranging from .409 in new wood to .492 g/cm^3 in 50-year-old wood. The average was .443 g/cm^3 on this low site Douglas-fir stand in western

Washington. Variation in specific gravity with age is likely to be slight, and can be ignored for the purposes of this model.[15]

A second assumption is that the specific gravities of Douglas-fir wood and bark are equal. The average specific gravity of Douglas-fir wood is .45 g/cm^3 (USDA For. Serv. 1974, Wood Handbook, p. 4-15). Smith and Kozak (1971) report a specific gravity of .439 g/cm^3 in Douglas-fir bark. Cassens (1974) measured the Douglas-fir outer bark specific gravity at .48 g/cm^3. I assumed average wood and bark specific gravity of .45 g/cm^3.

F2,7

F2,7 is the information flow from Douglas-fir foliage and branch nitrogen to foliage biomass and branch volume. This flow involves three steps. First, foliage and branch nitrogen is converted to biomass by the following regression equation, which is based on data from Turner (1975):

$$B_f = 167.488\ (N_f) \qquad R^2 = .99$$

where B_f is foliage and branch biomass in kg/ha and N_f is foliage and branch nitrogen in kg/ha. Figure 13 shows Turner's data and the regression line. Again, it is assumed that nitrogen concentration remains constant with stand age.

The second step is to partition the foliage and branch biomass

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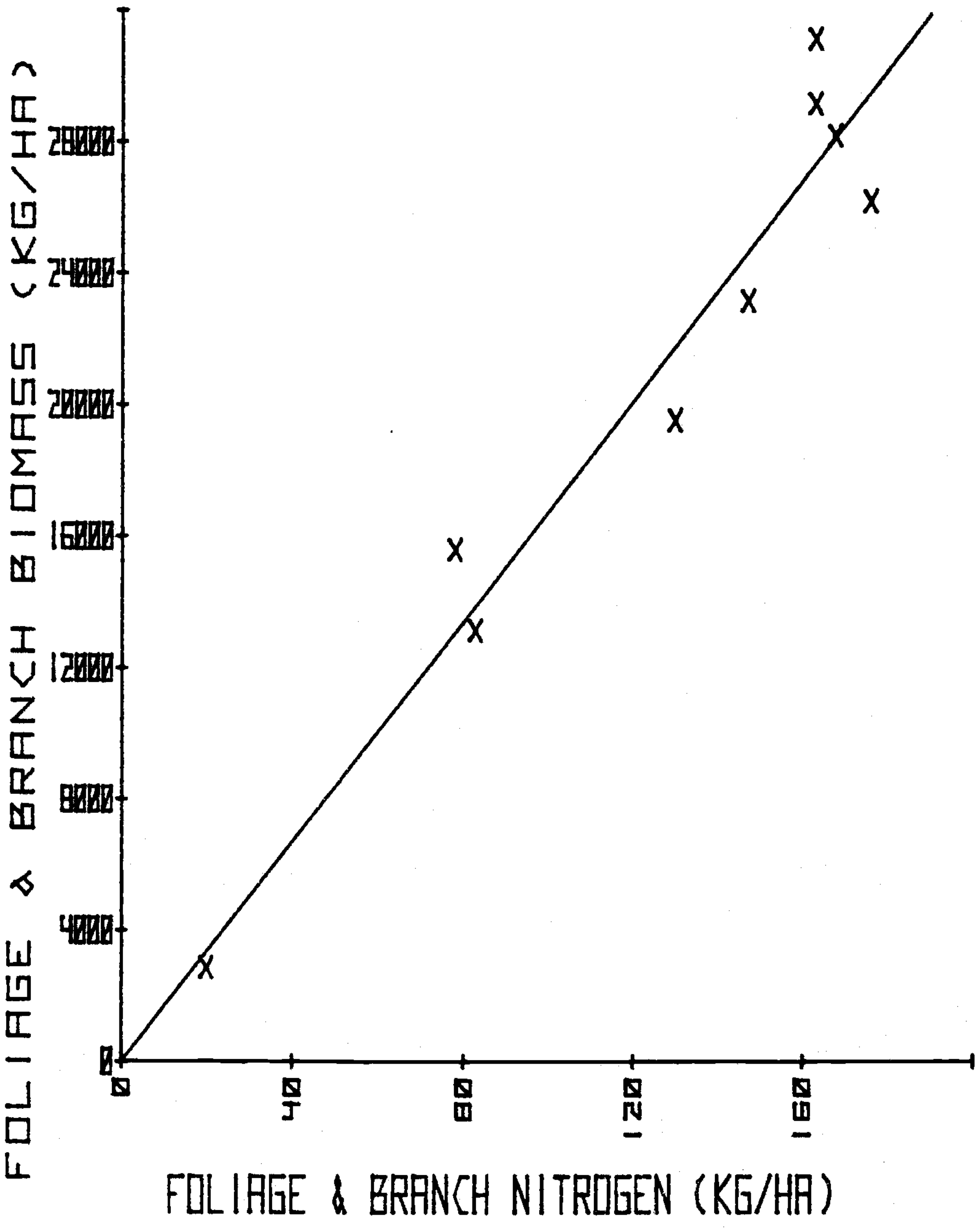
[15] M. D. McKimmy, 1980, personal communication.

FIGURE 13. Foliage and branch biomass as a function of foliage and branch nitrogen (X = data from Turner (1975); ___ = relationship used in the simulation).



into its two components. This is done by the following regression equation developed from Turner's data.

$$B_b = 1.6858\ (B_f^{.8752})\ (1.0001^{Bf}) \qquad R^2 = .99$$

where B_b is the branch biomass in kg/ha and B_f is the total foliage and branch biomass in kg/ha. See Figure 14 for a graph of the regression equation and Turner's data.

The third and final step involves the conversion from branch biomass to branch volume, using:

$$\text{volume } \frac{m^3}{ha} = \frac{\text{biomass } \frac{kg}{ha}}{\text{s.g. } \frac{g}{cm^3}} \times .001 \qquad \text{where s.g.} = .50\ g/cm^3$$

The specific gravity of Douglas-fir branches is assumed to average .50 g/cm^3 (McKimmy and Ching, 1968).[16]

2. Initial Stand Conditions

The model contains several assumptions concerning initial conditions at the start of the simulated stand's development. The first assumption is that the area was logged the previous year and the slash burned, leaving 10 kg/ha nitrogen in the forest floor. Since Turner (1975) measured 28 kg/ha in the forest floor of a nine-year-old stand, 10 kg/ha is reasonable as an initial condition.

Secondly, the initial soil nitrogen content is 3364 kg/ha.

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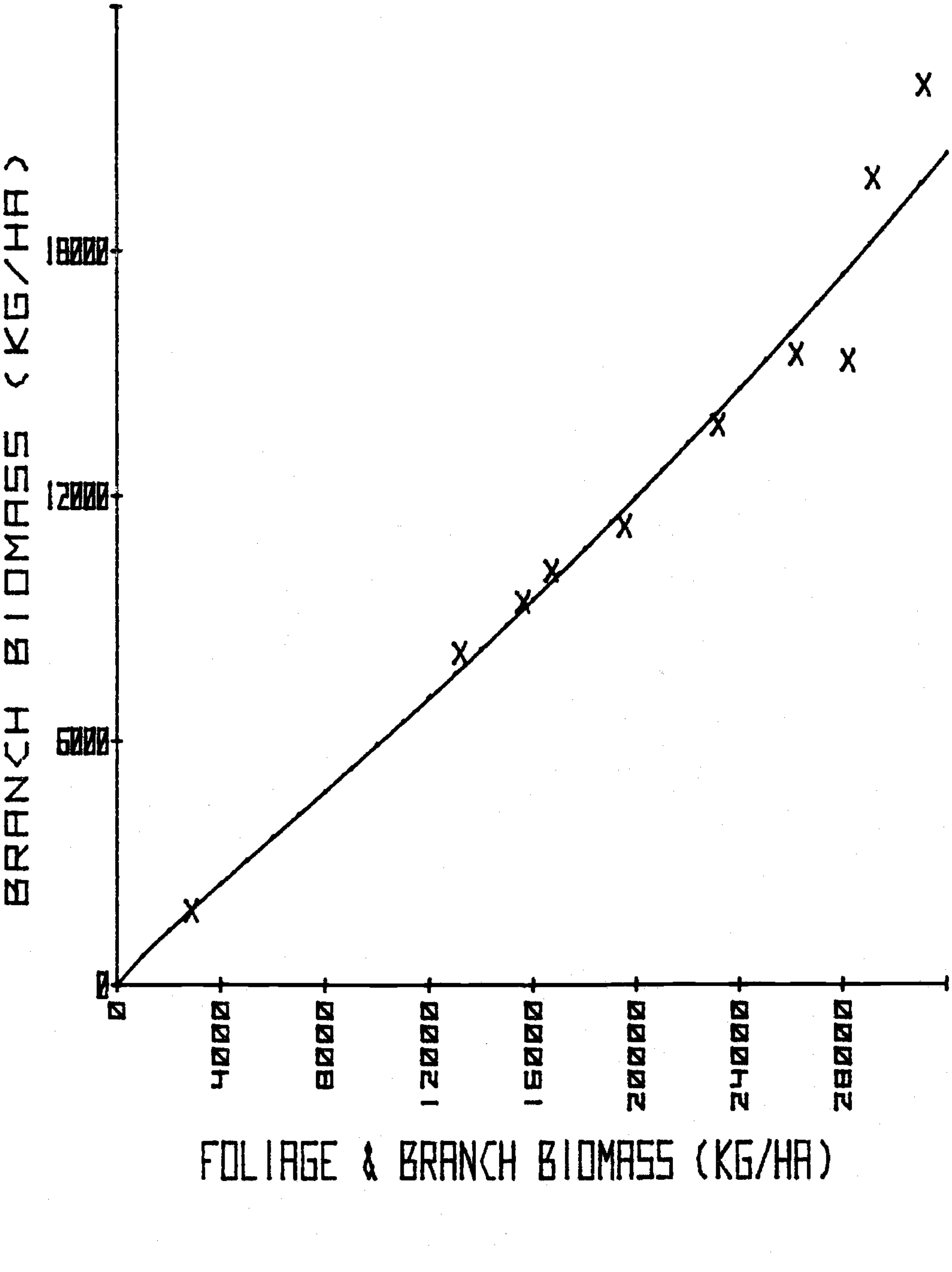
[16] Ibid.

FIGURE 14. Branch biomass as a function of the total foliage and branch biomass (X = data from Turner (1975); ___ = relationship used in the simulation).



This assumption was established in the following way. Grier and Cole (1972), in their study of a 34-year-old Douglas-fir stand at the Thompson Research Center, estimated a total soil nitrogen content of 2810 kg/ha. Given the previously defined flow rates for soil nitrogen additions and losses in the first 34 years, then soil nitrogen must be initialized at 3364 kg/ha to produce a value of 2810 kg/ha in year 34.

Thirdly, Douglas-fir nitrogen and volume are initialized to zero in all compartments (X1, X2, X6, and X7). The model assumes that the site is established with Douglas-fir seedlings at the start of simulated time.

A fourth assumption is an initial value of 30 kg/ha nitrogen in the understory vegetation. This assumes that some species invaded the site before the Douglas-fir seedlings were planted. Turner (1975) estimated an understory nitrogen content of 46 kg/ha in a nine-year-old stand. Therefore, 30 kg/ha at the time of stand establishment appears reasonable.

These initial conditions define the starting points of the mathematical model. They are used in combination with the previously established flow rates to develop the computer simulation model.

3. The Computer Simulation Model

The computer simulation model provides the solution to the mathematical model over time. The simulation is programmed in GASP IV, a FORTRAN-based simulation language (Pritsker, 1974). Forest growth and nitrogen cycling are continuously occurring processes, represented by the base model in a GASP IV continuous simulation program. Appendix A contains a listing of the program and definitions of the FORTRAN variables and subprograms. The core of the continuous simulation is a set of six difference equations which determine the values of the eight state variables over time (see Table V). Consider the following difference equation:

$$X1(t) = X1(t-1) + F5,1 - F1,4 - F1,0$$

where $X1(t)$ is the value of wood and bark nitrogen at time t years, $F5,1$ is the yearly rate of nitrogen uptake from the soil, $F1,4$ is the annual nitrogen litterfall rate and $F1,0$ is the yearly rate of nitrogen removal by harvesting. The difference equation is solved in two steps. First, the value of each flow rate is calculated for year t through a call to its respective FORTRAN subprogram. Then $X1(t)$ is computed as the value of the state variable in the previous year ($X1(t-1)$) plus the amount added by uptake minus the amounts lost by litterfall and harvesting. Values of the state variable and rates are stored for later output. Time is then advanced one year and the procedure of updating the state variable is repeated.

A unique feature of GASP IV is its ability to combine continuous

TABLE V. DIFFERENCE EQUATIONS USED IN THE MODEL.

$$X1(t) = X1(t-1) + F5,1 - F1,0 - F1,4$$

$$X2(t) = X2(t-1) + F5,2 - F2,0 - F2,4$$

$$X3(t) = X3(t-1) + F5,3 - F3,0 - F3,4$$

$$X4(t) = X4(t-1) + F0,4 + F4,5 + F2,4 + F3,4 - F4,0 - F4,5$$

$$X5(t) = X5(t-1) + F0,5 + F4,5 - F5,0 - F5,1 - F5,2 - F5,3$$

and discrete aspects in one simulation. The continuous part of the simulation has been described above. The discrete aspects are reflected in the occurrence of time events. A time event is something that happens at a scheduled time, for example, timber harvesting at the end of the rotation. The occurrence of a time event may change the values of certain state variables or flow rates. Continuing with the same example, a timber harvesting event causes an increase in the rate of nitrogen removal by harvesting, and changes the uptake and litterfall rates to zero. Therefore, the base model provides for the continuous functioning of the forest ecosystem, while the management decision variables represent the occurrence of discrete time events. The simulation results in a series of tables and graphs of the state variables and flow rates over time.

4. Validation of the Base Model

The base model simulation results of 120 years of growth and nitrogen cycling were compared to the literature. The first consideration, Douglas-fir simulated wood and bark volume, is within the range of values reported in the literature. Table VI shows comparisons between the simulated volume and several growth and yield studies of Douglas-fir in the Pacific Northwest. Simulated volumes are high for the young ages but close in the later years (80-120) compared to McArdle _et al_. (1961), Hoyer (1975) and Bruce _et al_. (1977). However, the simulated volume is for all trees,

TABLE VI. COMPARISON OF SIMULATED DOUGLAS-FIR WOOD AND BARK VOLUME WITH DATA FROM OTHER SOURCES.

Stand Age (yrs.)	Simulated Wood + Bark All trees Site IV	McArdle 1961 Wood Volume Trees 1.5"+DBH Site IV	Hoyer 1975 Wood Volume Trees 1.5"+DBH Site IV	Bruce et al. 1977 Wood Volume Trees 1.5"+DBH Site IV	Heilman 1961 Wood Volume All trees Site IV	Forristall 1954 Wood Volume All trees Sites II + III
20	2697	870	925			
25	3761			1895		
30	4767				660	4802
32	5120				660*	
35	5660					6880
38	6175				4000 13230	
40	6546	3560	4167			
45	7419			4604		
50	7981					5489
52	8270				4840	
60	9286	5880	7186			
65	9651			6662		
80	9963	7690	9527			
85	10058			8238		
100	10635	9000	11646			
105	10146			9492		
110	10407	9500				

TABLE VI. (CONT.)

115	10137		10031
120	9574	9920	
125			10523

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* Site V

including bark volume, while these three studies did not include the bark or trees less than 1.5 inches d.b.h.[17] This could account for the discrepancies in the younger ages. The simulated wood and bark volumes are close to but lower than Forristall's estimates (1954) of total volume in all trees. Forristall's study was of higher site quality stands, which would explain his higher volumes. The simulation produces wood and bark volumes which are generally much higher than Heilman's estimates (1961). This could be due to variability in sites and stand characteristics.

Secondly, as shown in Table VII, simulated wood and bark biomass is much higher than in Heilman's stands (1961). This is consistent with the higher simulated volumes previously mentioned. The simulated biomass at age 18 is also higher than Webber's data (1973), but this might be explained by site differences, Webber's site being on Vancouver Island. Fujimori _et_ _al_. (1976), in a western Oregon study, reported a much higher biomass than that produced by the simulation, but again, this could be attributed to differences in sites.

Wood and bark nitrogen content is a third point of validation. Table VIII indicates that the simulated values are in close agreement with Webber's 18-year-old stand (1973). However, Heilman's data (1961) are much lower than the simulated wood and bark nitrogen. Since Heilman's biomass data were considerably lower than the simulated biomass, lower nitrogen values would also be expected.

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[17] Diameter at breast height; 4.5 feet high.

TABLE VII. COMPARISON OF SIMULATED DOUGLAS-FIR WOOD AND BARK BIOMASS WITH DATA FROM OTHER SOURCES (units are in kg/ha).

age (yrs.)	WOOD AND BARK BIOMASS			
	Present Simulation Site IV	Heilman (1961) Site IV	Fujimori *et. al.* (1976) Blue River, OR	Webber (1973) mid-low Site IV
18	65,580			49,281
30	143,500	22,854		
32	154,700	23,347*		
38	188,400	69,794 130,016		
52	255,900	174,725		
110	326,100		579,400	

* Site V

TABLE VIII. COMPARISON OF SIMULATED DOUGLAS-FIR WOOD AND BARK NITROGEN WITH DATA FROM OTHER SOURCES (Units are in kg/ha).

	WOOD AND BARK NITROGEN		
Age (yrs.)	Present Simulation	Heilman (1961) Site IV	Webber (1973) mid-low Site IV
18	65.7		64.4
30	137.1	20.7	
32	147.2	17.9*	
38	177.5	71.5 108.7	
52	237.7	155.8	

* Site V

The fourth variable, simulated foliage and branch nitrogen, is generally in agreement with Heilman's data (1961), as shown in Table IX. The understory nitrogen is the fifth comparison. Table X shows that the simulated understory nitrogen at age 30 is almost equal to Heilman and Gessel's value (1963). But with increasing age, the simulation produces greater amounts of understory nitrogen than Heilman and Gessel found in their stands. This could be explained by differences in stand characteristics between sites.

A sixth point of validation is forest floor nitrogen. As indicated in Table XI, the simulated forest floor nitrogen is generally slightly less than Heilman's estimates (1961) and much less than Webber's (1973). But when compared to Tarrant and Miller's 35-year-old Wind River site in western Washington (1963), the simulated values are a little high. The simulated forest floor nitrogen at 100 years is close to the range reported by Youngberg (1966), but is much higher than Youngberg's average for these western Oregon coast range sites. The simulation is also higher than Gessel and Balci's average forest floor nitrogen content on 80 to 120-year-old western Washington sites (Gessel and Balci, 1965). The close agreement between Grier and McColl's data (1971) and the simulated forest floor nitrogen is not unexpected, since Grier and McColl's site was in the same watershed as sampled in Turner's study.

TABLE IX. COMPARISON OF SIMULATED DOUGLAS-FIR FOLIAGE AND BRANCH NITROGEN WITH DATA FROM OTHER SOURCES (units are in kg/ha).

Age (yrs.)	FOLIAGE & BRANCH NITROGEN	
	Present Simulation mid-site IV	Heilman (1961) Site IV
18	49.6	
30	102.2	91.2
32	111.4	65.6*
38	136.4	124.7 151.4
52	159.4	205.0

* Site V

TABLE X. COMPARISON OF SIMULATED UNDERSTORY NITROGEN WITH DATA FROM OTHER SOURCES (units are in kg/ha).

Age (yrs.)	UNDERSTORY NITROGEN	
	Present Simulation	Heilman & Gessel (1963)
30	58	59
32	52	21
38	37	10
52	19	0

TABLE XI. COMPARISON OF SIMULATED FOREST FLOOR NITROGEN WITH DATA FROM OTHER SOURCES (units are in kg/ha).

Age (yrs).	Simulation	Gessel & Baki 1965	Tarrant & Miller 1963	Grier & McColl 1971	Youngberg 1966	Heilman 1961	Webber 1973
18	94						413 140
30	193					372	
32	203					184	
35	212		158				
38	224					273 266	
40	232			216			
52	328					657	
Average 100	580				169-501 274 Avg.		
80-120	547-653	193					

The last variable considered is total soil nitrogen. Table XII shows comparisons between the simulation and the literature. Simulated soil nitrogen is generally in the range of values reported for Tarrant and Miller's 30-year-old stand (1963), Forristall's 50-year-old stand in Lee Forest, western Washington (1954), Johnson's 47-year-old stands (1979), Webber's 18-year-old stand (1973) and Heilman and Gessel's 30 to 52-year-old stands (1963). Since site differences obscure any trends in total soil nitrogen with time, this validation can only note that the simulated soil nitrogen values are within the range of values reported in the literature.

The comparison of the simulated forest conditions with the literature has revealed the extensive variation in sites and the lack of quantitative data on nitrogen cycling trends over time. However, it has been established that the base model simulates forest conditions within the range of realistic possibilities.

C. Addition of Management Decision Variables

The second stage of model development involved addition of the management decision variables: Douglas-fir rotation length; timber utilization standard; slash treatment; and fertilization. The resultant changes in the base model are discussed below.

TABLE XII. COMPARISON OF SIMULATED TOTAL SOIL NITROGEN WITH DATA FROM OTHER SOURCES (units are in kg/ha).

Age (yrs.)	Simulation mid-site IV	Tarrant & Miller (1963) Site IV	Forristall (1954) Site III	Johnson (1979) Site IV	Webber (1973) mid-low Site IV	Heilman & Gessel (1963) Site IV
18	3097				3501 2680	
30	2865	3018				2146
32	2842					1948*
38	2780					2938 3070
47	2678			3240 2820		
50	2641		3727			
52	2616					1596

* Site V

1. Timber Harvesting

The addition of timber harvesting permits simulation of the effects of several rotations of forest management. Douglas-fir rotation length may be set at any age up to 120 years. The choice of utilization standard includes harvesting the bole only or whole tree harvesting (excluding roots). Harvesting of the boles only assumes a six percent unmerchantable top, based on Hatton and Keays (1972). In whole tree harvesting the entire wood and bark volume and 90 percent of the foliage and branches are removed from the site. There are two slash treatment options: leave the slash in place; or remove (or burn) 90 percent of the slash. Slash burning is considered to have the same effect as removing 90 percent of the slash from the site. This is based on reported losses of 90 to 92 percent of the nitrogen content of slash as a result of light to heavy slash burns at the Thompson Research Center (Grier, 1972). The following flow rates are affected by timber harvesting:

F1,0; F6,0; F1,4; and F2,0; F7,0; F2,4

When a bole only harvesting event occurs, 94 percent of the wood and bark nitrogen and volume is removed from the site (F1,0; F6,0). The remaining six percent is transferred to the forest floor (F1,4). The rate of removal of foliage and branch nitrogen and volume from the site remains at zero (F2,0; F7,0), since the entire amount is transferred to the forest floor as slash (F2,4). Therefore, with bole only harvesting:

F1,0 = 0.94 (X1)

F1,4 = 0.06 (X1)

F6,0 = 0.94 (X6)

F2,0 = 0.0

F2,4 = X2

F7,0 = 0.0

If whole tree harvesting occurs, the total amount of wood and bark nitrogen and volume is removed from the site. Of the total foliage and branch nitrogen and volume, 90 percent is harvested. The remaining 10 percent is considered impractical to remove and is added to the forest floor as slash. Whole tree harvesting, then, causes the following changes:

F1,0 = X1

F1,4 = 0.0

F6,0 = X6

F2,0 = 0.90 (X2)

F2,4 = 0.10 (X2)

F7,0 = 0.90 (X7)

F3,0 and F3,4

The effects of harvesting on understory nitrogen depend on the method of slash treatment. If slash is removed or burned, then

I assume 90 percent of the understory nitrogen is also removed (F3,0). The remaining 10 percent is added to the forest floor (F3,4). So, with slash removal:

F3,0 = 0.90 (X3)

F3,4 = 0.10 (X3)

If the slash is left in place, then the entire understory nitrogen is added to the forest floor. This assumes logging activities have knocked down the understory vegetation. Hence:

F3,0 = 0.0

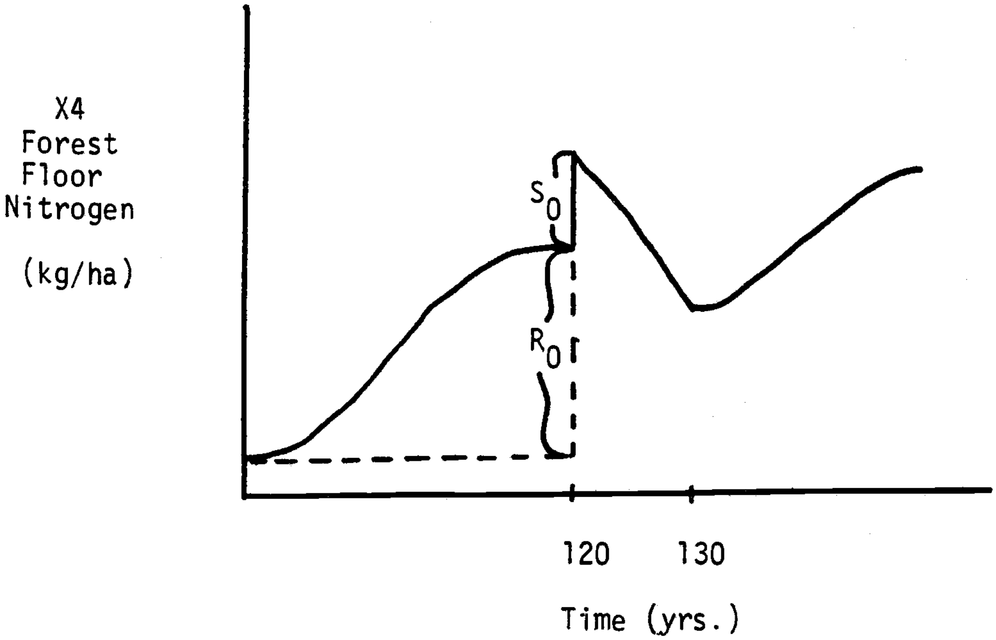
F3,4 = X3

F4,0 and F4,5

When the method of slash treatment is slash removal or burning, 90 percent of the total forest floor nitrogen is lost (G2 = 0.90 (X4)). If the slash is left in place, then F4,0 is not affected (G2 = 0.0).

After harvesting, the forest floor has two components, as shown in Figure 15. The first is the nitrogen added as slash, designated S_0. The second is the nitrogen remaining in the forest floor from the previous rotation, indicated by R_0. The transfer of nitrogen from both forest floor components to the soil (F4,5) is accelerated if slash is left after harvesting. In a 32-year-old Douglas-fir stand at the Thompson Research Center, Cole and Gessel (1965) found an increase in this transfer to 2.75 times the control rate

FIGURE 15. Effect of Timber Harvesting on Forest Floor Nitrogen when Slash is Left in Place (S_0 is the nitrogen added as slash; R_0 is the nitrogen remaining from the previous rotation; the rotation length is 120 years.)



one year after clearcutting. They did not indicate the relative contribution from each forest floor component. When the slash is left, I assume 90 percent of the original slash nitrogen will decompose within ten years of harvesting. This is based on the large quantities of rapidly decomposing tree tops, needles and small branches which constitute the majority of the slash.[18] After ten years the accelerated decomposition effect is assumed to be no longer significant.

The following method was used to determine the annual rate of slash nitrogen added to the soil during the ten-year period.

$$S_t = k\ S_{t-1}$$

where S_t represents nitrogen in the slash at time t and k is a constant. Then,

$$S_t = k\ S_{t-1} = k\ (k\ S_{t-2}) = \ldots$$

so, $$S_t = k^t\ S_0$$

This indicates that slash nitrogen at time t is a function of the original nitrogen in the slash, S_0. Assuming ten percent of the original amount is left after ten years,

$$.10\ S_0 = k^{10}\ S_0$$

---

[18] This assumption was made in consultation with Kermit Cromack, Jr. and William K. Ferrell.

then, $k = .7943$

Therefore, the amount of nitrogen in the slash during any of the ten years after harvesting is given by:

$$S_t = .7943^t\ S_0$$

The rate of nitrogen lost from the slash each year is represented by α, where

$$\alpha = \frac{S_t - S_{t-1}}{S_{t-1}}$$

Since $S_t - S_{t-1} = \alpha\ S_{t-1}$

$$S_t = \alpha\ S_{t-1} + S_{t-1}$$

$$S_t = (\alpha + 1)\ S_{t-1}$$

This corresponds to the first difference equation:

$$S_t = k\ S_{t-1} \quad \text{where } \alpha + 1 = k$$

Since $k = .7943$, $\alpha = -.2057$

The transfer of slash nitrogen to the soil during each of the ten years after harvesting is given by $.2057\ S_{t-1}$.

If the slash is left, the nitrogen remaining in the forest floor from the previous rotation, R_0, is also subject to an accelerated transfer to the soil. This effect is due to: (1) accelerated decomposition as the site is opened up to more sunlight; (2) the mechanical incorporation of forest floor nitrogen into the soil by harvesting and yarding equipment (Cromack et al., 1978); and (3) a possible increase in the proportion of nitrogen uptake from the forest floor by the seedlings.[19] Without the accelerated transfer, forest floor nitrogen accumulates to unrealistic levels after three or four rotations. The increase in nitrogen transfer to the soil is expressed as a function of rotation length. It is assumed that with shorter rotations, proportionately more needle and fine litter is found in the forest floor. These finer materials will decompose faster than the greater proportions of woody material that result from longer rotations. Due to the lack of data, I assumed that with rotation lengths of 100 to 120 years, 25 percent of the nitrogen accumulated in the previous rotation is transferred to the soil in the first ten years after harvesting. With rotation lengths between 65 and 99 years, 50 percent is transferred; when the rotation is less than 65 years, the percentage increases to 65 percent. The previously described method resulted in the following rates:

Rotation length (yrs.)	Transfer of remaining nitrogen, R_t, to the soil (kg/ha/yr)
1- 64	$.0967\ R_{t-1}$
65- 99	$.0670\ R_{t-1}$
100-120	$.0284\ R_{t-1}$

---

[19] Since forest floor uptake is a component of F4,5, this would result in an increase in the flow rate to the soil.

The base rate of F4,5 is applied to new additions of litter nitrogen during the ten-year period of stand establishment. The accelerated transfer due to harvesting is then calculated for each component, S_t and R_t, and added to the base rate.

F5,0

Losses of soil nitrogen due to erosion (G3) and leaching (G5) are increased by timber harvesting. Swanson estimated nitrogen erosional losses of 0.088 and 2.744 kg/ha/yr in the first and second years after clearcutting in Watershed 10 of the Andrews Forest.[20] Return to the preharvest rate of erosion was expected to take ten years (Swanson, Fredriksen and McCorison, 1980 (in press)). Based on the average of Swanson's data, I assume that bole only harvesting with slash left in place causes an increase in the rate of soil nitrogen lost in erosion to 1.5 kg/ha/yr. This response gradually returns to the preharvest rate in ten years. If slash is removed or burned, the erosional loss increases to 2.9 kg/ha/yr for a ten-year duration. This assumption reflects the average of Fredriksen's estimates (1971) of 3.8 and 1.9 kg/ha/yr in the two years following clearcutting and slash burning in the Andrews Forest.

In comparison to bole only harvesting, whole tree harvesting

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[20] F. J. Swanson, ibid.

is expected to further increase nitrogen erosional losses. Due to the lack of data, I assumed whole tree harvesting results in a doubling of the erosional loss over bole only harvesting. These changes to the base model are summarized as follows:

	bole only harvesting	whole tree harvesting
leave slash	G3 = 1.5	G3 = 3.0
remove slash	G3 = 2.9	G3 = 5.8

Soil nitrogen leaching losses also increase after harvesting. Kimmins and Feller (1976) reported an average nitrogen leaching loss of 2.4 kg/ha the year after clearcutting a second-growth Douglas-fir stand in British Columbia. This represented a four-fold increase over the control. On a western Oregon old-growth Douglas-fir site, Fredriksen (1971) estimated a post-harvesting nitrogen leaching loss of .26 kg/ha/yr, or 3.3 times the control rate. Clearcutting of a 32-year-old Douglas-fir stand at the Thompson Research Center resulted in an average soil nitrogen solution loss of 1.18 kg/ha/yr (about two times that of the control) (Cole and Gessel, 1965). I assumed that both whole tree and bole only harvesting result in a doubling of the base model's nitrogen leaching rate, to G5 = 6.2 kg/ha/yr. This is based on Cole and Gessel's data, which were from the same watershed as used in Turner's study. Using estimates by Swanson _et al_. (1980 (in press)), the increase will persist for five years, gradually returning to the base rate the fifth year after harvesting.

I assumed that both removing (or burning) the slash and leaving the slash in place result in the same increase in nitrogen leaching, 6.2 kg/ha/yr. This is supported by a study of slash burning at the Thompson site which revealed little nitrogen released in the soil solution after burning (Grier, 1972). Although Kimmins and Feller (1976) reported an increase in leaching to 5.1 kg/ha nitrogen the first year after cutting and burning, this is still lower than the 6.2 kg/ha/yr used in the model. Fredriksen also estimated an increase in nitrogen solution losses up to 2.4 kg/ha/yr as a result of slash burning. Again, this is less than the rate assumed by the model.

F5,1; F5,2 and F5,3

When timber is harvested, the rates of nitrogen uptake by the vegetation (F5,1; F5,2; F5,3) are set at zero for that year. The year after harvesting, Douglas-fir regeneration automatically takes place and the uptake rates return to their respective base levels.

2. Fertilization

There are three fertilization options. The first is no fertilization. The second is the addition of 220 kg/ha of nitrogen as urea when the stand is 36 years old. The use of 220 kg/ha is based on commonly practiced application rates (Bengtson, 1979; Miller and Fight, 1979). According to Bengtson, nitrogen fertilizer is usually applied to stands between 15 and 60 years old. The application of fertilizer at 36 years old is within Bengtson's range and is also the average age used in several fertilization studies at the Thompson site (Cole and Gessel, 1965; Turner, 1975; Crane, 1972).

The third option is to alternate Douglas-fir rotations with either 15 or 40-year red alder rotations. The net nitrogen additions during the alder rotation are considered a form of fertilization of the subsequent Douglas-fir stand. The choices of alder rotation legnth are based on 10 to 15-year rotations for pulpwood and 28 to 37 years for sawlogs and peelers (DeBell, Stand and Reukema, 1978).

When urea fertilization occurs, flow rates are affected in the following way. Fertilization additions to the forest floor increase to 220 kg/ha nitrogen (G14 = 220.0). Of this amount, 208 kg/ha is transferred to the soil within the first year after fertilization (F4,5 = 208.0). Cole and Gessel (1965) found 174 kg/ha nitrogen in solution transferred from the forest floor to the soil ten months after fertilization. Crane (1972) reported a similar transfer of 214 kg/ha in the five-month period following fertilization. The assumed rate of 208 kg/ha is between these two values.

In the model, the application of urea fertilizer causes a nitrogen volatilization loss of 9.3 kg/ha from the forest floor. This is based on Crane's findings (1972) of 9.5 kg/ha volatilized during the application of 224 kg/ha of nitrogen as urea.

The addition of urea causes an increase in the rates of uptake of soil nitrogen by the vegetation. Turner (1975) found that Douglas-fir wood, branch and foliage uptake of fertilized stands averaged 168 percent of the base rate. The increased uptake gradually declines to the base level ten years after fertilization. Miller and Pienaar (1973) reported continuing growth responses seven years after fertilization of a low-site stand in the Wind River Experimental Forest in western Washington. Fertilization response is likely to last 10 to 15 years after application, according to Miller and Fight (1979). Foliage and branch uptake (F5,2) is also assumed to increase to 168 percent of its base rate, with the effect continuing for seven years. An initial ten-year response period was used for the foliage and branches, but the results were unrealistic. In the model, understory uptake (F5,3) increases after fertilization. Turner did not measure understory response to fertilization, so I assume understory uptake occurs at 125 percent of its base rate for seven years after fertilizer application.

Urea fertilization has the initial effect of increasing needle retention and therefore decreasing leaf litterfall. The first year after fertilization, Turner (1975) estimated leaf litterfall at 92.2 percent of the control. Therefore, the model assumes a decrease in foliage and branch litterfall (F2,4) to 92.2 percent of the base rate the year after fertilization.

A last effect of urea fertilization is the loss of nitrogen by leaching beyond the rooting zone (G5). Crane (1972) reported 11.2 kg/ha of nitrogen was lost in solution when rainfall occurred immediately after fertilization. He stated, however, that in average situations there is little loss of fertilizer nitrogen by leaching. In the first year after fertilization, Cole and Gessel (1965) found a 27.7 percent increase in nitrogen solution losses from the soil. These losses were expected to continue until the establishment of a new canopy. The model assumes the soil nitrogen lost by leaching will increase to 127 percent of the base rate for five years after fertilization.

The red alder fertilization option creates several changes in the base model. When an alder rotation is in progress, the only two state variables monitored are forest floor and soil nitrogen. This assumes that the effect of the alder on subsequent Douglas-fir growth can be approximated by the net increment of nitrogen added to the forest floor and soil by the alder. Net increment is the total nitrogen addition from precipitation and fixation, minus the alder's growth requirements and minus leaching, erosion and denitrification losses. For model simplification purposes, I did not include any effects of alder harvesting or site preparation on the next Douglas-fir rotation. Any such effects are indirectly included in the "average" estimates used for the net alder additions. However, I did assume that slash would not be burned at the end of an alder rotation.

When an alder time event occurs all the flow rates in the model become zero, except for the nitrogen fixation additions to the forest floor (G9) and to the soil (F0,5). Table XIII summarizes estimates from the literature of net annual nitrogen additions to a site by red alder. The additions include the effect of nitrogen-rich alder litter, as well as nitrogen fixation. Based on Atkinson, Bormann and DeBell (1979), the model assumes the following rates will occur during an alder rotation:

Alder rotation length (yrs)	Soil nitrogen additions (kg/ha/yr)	Forest floor nitrogen additions (kg/ha/hr)
15	F0,5 = 24.0	F0,4 = 17.2
40	F0,5 = 26.5	F0,4 = 15.3

The above forest floor additions are consistent with values estimated by Cole, Gessel and Turner (1978), while the soil nitrogen additions are conservative. Although the model represents the transfers as constant over the length of the alder rotation, nitrogen fixation rates vary with the age of the alder, reaching

TABLE XIII. NITROGEN ADDITIONS TO THE FOREST FLOOR AND SOIL FROM RED ALDER.

Number of Years of Alder	Net annual nitrogen increment (kg/ha/yr)			Reference
	FOREST FLOOR	SOIL	TOTAL	
8	22.3	27.9	50.2	Atkinson, Bormann and DeBell 1979; near Olympia, Washington
13	17.2	24.0	41.2	"
32	15.3	26.5	41.8	"
10	18.0			Turner, Cole and Gessel 1976: Thompson Research Center; alder aged 26-36 years
40	60.8	110.6	171.4	Tarrant, Lu, Bollen and Franklin 1969; Cascade Head Exp. Forest, Oregon
30		18.7		Franklin, Dyrness, Moore and Tarrant 1968; Cascade Head
38	18.4	57.4	75.8	Cole, Gessel and Turner 1978; Thompson Research Center

a maximum at about 20 years of age (Tarrant *et al*., 1969).

Atkinson, Bormann and DeBell (1970) assumed a six percent growth increase in Douglas-fir stands that followed a 13-year alder rotation, and an eight percent increase following a 32-year alder rotation. These estimates were based on the assumption that alder nitrogen is only 25 to 65 percent equivalent to fertilizer nitrogen. In the model, if the preceding rotation consisted of alder, the rates of uptake of soil nitrogen by the vegetation are increased by the following amounts:

Alder rotation length	Increase in nitrogen uptake relative to the base rate		
	F5,1	F5,2	F5,3
15	13.0%	0.8%	0.3%
40	15.0%	1.0%	0.4%

The above increases in uptake rates are specific to a 60-year Douglas-fir rotation. They result in six and eight percent increases in Douglas-fir and understory nitrogen and volume following 15 and 40-year alder rotations, respectively. Relative increases in uptake rates for other Douglas-fir rotations were not estimated, although this could be accomplished for any desired rotation length.

3. Validation of Management Effects

Model validation can take several forms. The lack of a long-term data base precludes the type of validation that would compare the model's predictions of long-term management effects with the real world system. Rather, Forrester's (1961) rationalistic approach to model validation is more appropriate. If the individual assumptions presented in the previous section are accepted and their connections to each other are logical, then the validity of the model is accepted.

The assumptions used in developing the management aspects of the model have been well documented. Their bases lie in the available sources of data concerning timber harvesting and fertilization effects on the forest ecosystem. In most cases the nature of the data was short-term. However, the existence of longer term data on urea fertilization allows comparisons with the model's predicted fertilization growth response.

Data from the Regional Forest Nutrition Research Project indicated an average Douglas-fir growth gain of 364 cu ft/acre for the four-year period after fertilizing site IV lands with 224 kg/ha nitrogen as urea (Turnbull and Peterson, 1976). This compares with the model's predicted four-year gain of 516 cu ft/acre. The Project's six-year growth trends showed a 34 percent increase in mean gross total volume growth (College of Forest

Resources, 1979), compared to a 68 percent increase predicted by the model. The model's growth increases are much higher than those indicated by the Regional Forest Nutrition Research Project. This may be due to several factors, including the averaging effect of the Project's data or the model's possible overestimation of increases in nitrogen uptake rates with fertilization.

In another study, the net volume growth in a 35-year-old site V Douglas-fir stand increased from 740 to 1200 cu ft/acre in the seven-year period following application of 157 kg/ha nitrogen as ammonium nitrate (Miller and Pienaar, 1973). This constituted a 62 percent increase in growth. In the same study, fertilization with 314 kg/ha nitrogen resulted in a growth increase from 740 to 1470 cu ft/acre over the seven years, a 99 percent increase. The simulation produces a 68 percent net volume growth increase, from 1290 to 2170 cu ft/acre in the seven years after urea fertilization with 224 kg/ha nitrogen. Although the simulated volumes are higher, the relative growth response of a 68 percent gain is within the range of Miller and Pienaar's findings.

Heilman and Gessel (1963) reported the biomass growth response of a 30-year-old site IV Douglas-fir stand subjected to repeated urea fertilizations. The first year 224 kg/ha nitrogen was applied, followed by 112 kg/ha in each of the next three years. Eight years after the initial fertilization, a 53 percent increase in total tree biomass was found. The simulation produces a 17 percent increase in total Douglas-fir biomass ten years after fertilization. It seems reasonable to expect Heilman and Gessel's response due to the initial 224 kg/ha application to be within the range of the 17 percent response predicted by the simulation.

In summary, the model represents the effect of fertilization on growth by a 68 percent increase in nitrogen uptake rates. Although this leads to net volume growth increases that are higher than those found in the Regional Forest Nutrition Research Project, the relative growth response seems consistent with Miller and Pienaar's and Heilman and Gessel's findings.

III. RESULTS AND DISCUSSION

The research questions were addressed by using the model to compare management prescriptions for their effects on long-term productivity. The range of prescriptions and the results follow.

A. Description of Management Prescriptions

A prescription is represented by the choice of management variables. For any given rotation length there are 16 possible combinations of utilization standards, methods of slash treatment and fertilization practices, as shown in Figure 16. The choice of simulated prescriptions was based on the need to address the following questions:

1. What are the long-term trends in the indicators of forest productivity* as rotation length is varied?
2. How does the choice of timber utilization standard affect the productivity indicators?
3. What effect does the method of slash treatment have on the indicators of long-term productivity?
4. How does the choice of fertilization practice affect the productivity indicators?

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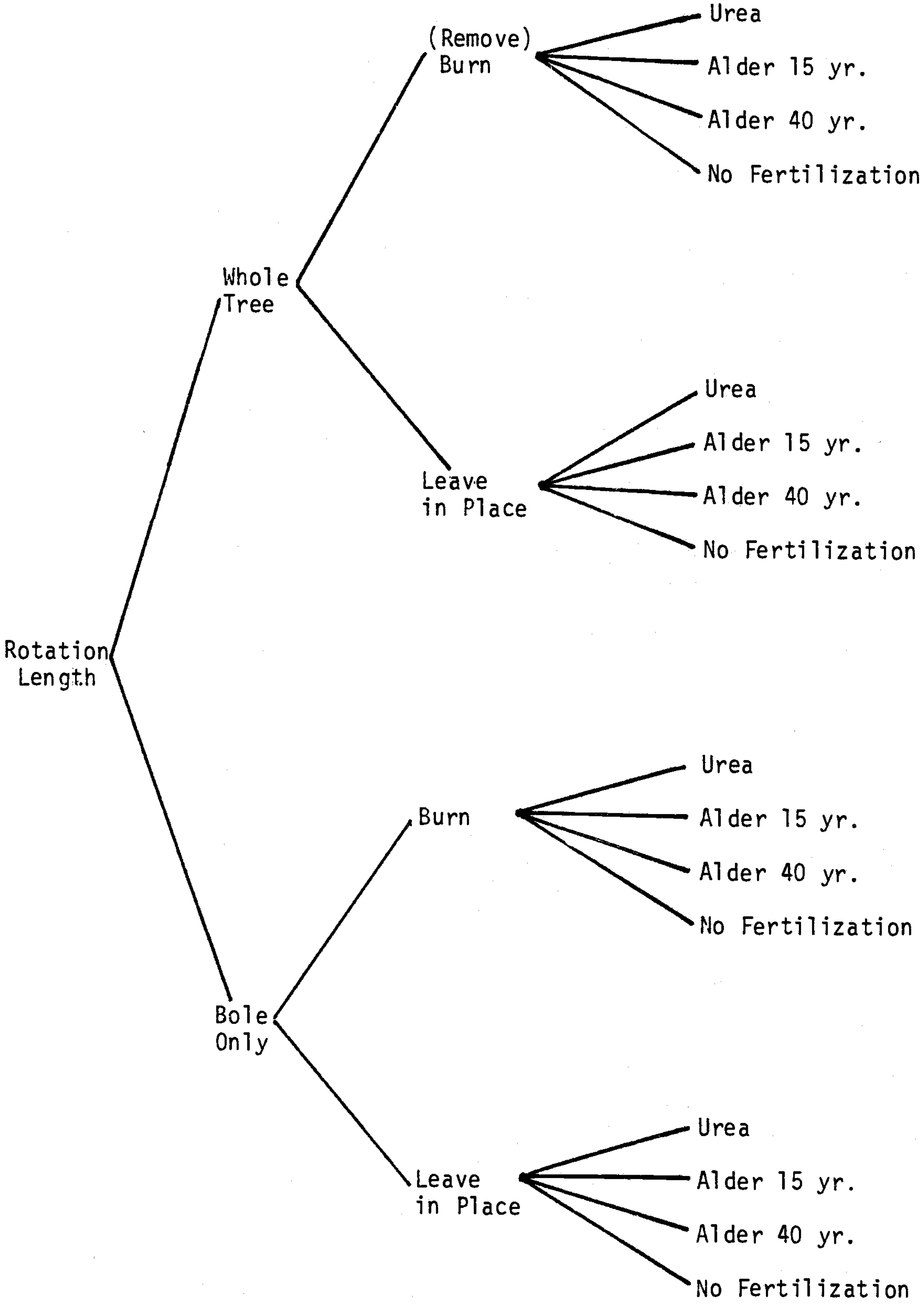
* The indicators of long-term forest productivity are:

1. total soil nitrogen
2. forest floor nitrogen

FIGURE 16. The Possible Combination of Management Variables.



3. nitrogen in the Douglas-fir and understory vegetation
4. nitrogen losses from vegetation removal and slash treatment
5. Douglas-fir timber volumes (both standing volume and volume removed by harvesting)
6. the difference in nitrogen additions to and losses from the ecosystem.

Three groups of prescriptions were analyzed. The first represented short Douglas-fir rotations of 50 to 60 years. The second group reflected medium length, 90-year rotations while the third was composed of longer, 120-year rotations. Figure 17 summarizes the 15 prescriptions and designates each by its model run.

Prescriptions were simulated for 360 years, with the exception of the 50-year rotation, which was run for 350 years. The presentation and discussion of the results follow.

B. Results and Discussion

1. Forest Floor and Total Soil Nitrogen

Simulated trends in forest floor and soil nitrogen are represented in both graphical and tabular form. Figure 18 shows the results for run 13, which evaluated a prescription of 120-year rotations, harvesting of boles only, slash left in place and no fertilization. The 120 years of the stand's development caused a steady decline in soil nitrogen. Note that the most rapid rate

FIGURE 17. Simulated Prescriptions

Run Number	Douglas-fir Rotation Length	Utilization Standard		Slash Treatment		Fertilization			
		Whole Tree	Bole Only	Remove (Burn)	Leave	Urea	Alder		None
							15 yr.	40 yr.	
1	60	X		X		X			
2	60		X	X		X			
3	60	X		X					X
4	60		X	X					X
5	60	X			X				X
6	60	X		X			X		
7	60	X		X				X	
8	90	X		X		X			
9	90		X	X		X			
10	90		X	X					X
11	90		X		X				X
12	120		X	X					X
13	120		X		X				X
14	120		X	X		X			
15	50	X		X					X

Figure 18. Simulated Forest Floor and Soil Nitrogen; Run 13: 120 yr. rotation; bole only harvesting; leave slash; no fertilization (4 = forest floor nitrogen (X4); 5 = soil nitrogen (X5)).

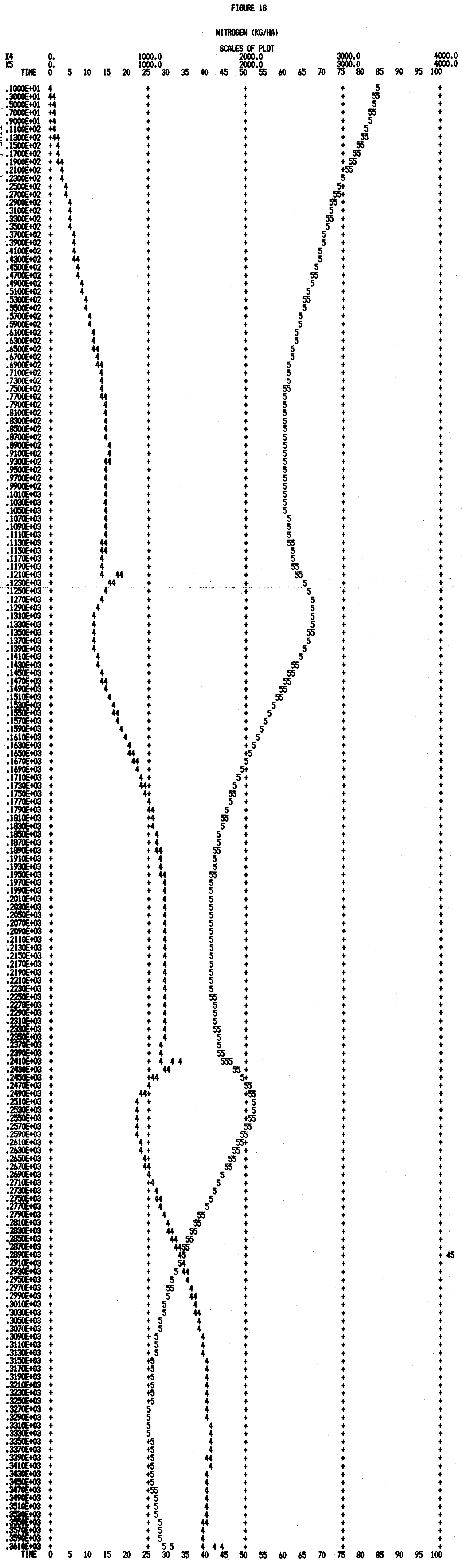


Figure 18. Simulated forest floor and soil nitrogen; Run 13.

of decline occurred during the first 40 years, corresponding to the period before canopy closure. The practices of harvesting only the boles and leaving the slash resulted in an increase in the forest floor nitrogen immediately after harvesting. Accelerated decomposition of the slash and remaining forest floor materials had the net effect of increasing soil nitrogen for 15 years after clearcutting. This reduced the forest floor nitrogen during the post-harvesting period. The higher accumulation of forest floor at the end of the second rotation caused greater additions to the soil compared to the first rotation.

Figure 19 indicates the results of run 1, which simulated 60-year rotations, whole tree harvesting, slash removal and urea fertilization. The shortening of the rotation length to 60 years produced a more rapid decline in soil nitrogen than in the 120-year rotation. Under the assumption that growth rates in successive rotations were the same as in the first, the soil nitrogen variable decreased to zero after 263 years of this management prescription. Whole tree harvesting and removal of the slash caused a decrease in forest floor nitrogen and the continued depletion of nitrogen in the soil. Fertilizer addition to the 36-year-old stand resulted in an increase in soil nitrogen, but was not sufficient to offset the losses due to shorter rotations, whole tree harvesting and slash removal.

Figure 19. Simulated Forest Floor and Soil Nitrogen; Run 1: 60 yr. rotation; whole tree harvesting; remove slash; urea fertilization (4 = forest floor nitrogen (X4); 5 = soil nitrogen (X5)).

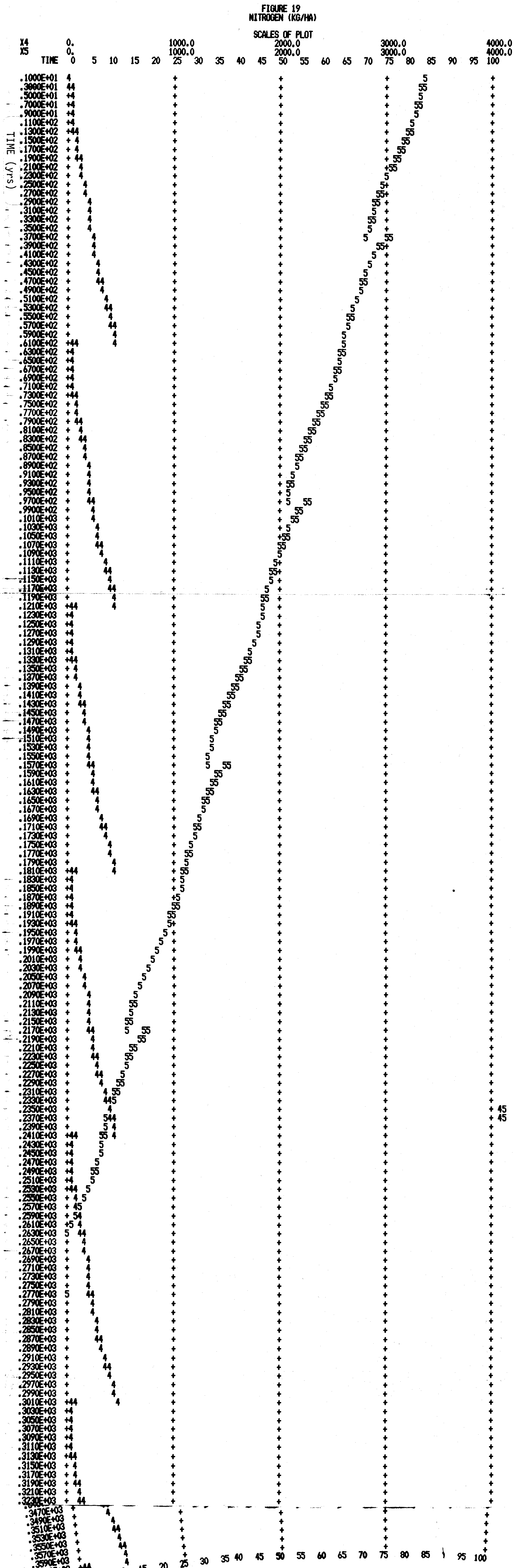


Figure 19. Simulated forest floor and soil nitrogen; Run 1.

Figure 20 shows the effect of 60-year Douglas-fir rotations with whole tree harvesting and slash removal, followed by 15-year alder rotations. The presence of alder caused an increase in the forest floor and soil nitrogen. This greatly reduced the total drain on the soil nitrogen due to the 60-year whole tree harvesting and slash removal practices.

The graphical results give examples of the nature of the trends in forest floor and soil nitrogen with several management prescriptions. Comparison among all of the prescriptions is facilitated by the use of tables. Table XIV summarizes the effects of simulated prescriptions on the forest floor. Nitrogen accumulation is expressed as total accumulation per rotation, annual accumulation per rotation and total accumulation over the 360-year period. The total and annual transfers of forest floor nitrogen to the soil are also shown. Simulated soil nitrogen is presented in Table XV. The difference in the amount of soil nitrogen between the beginning and end of the rotation is an indication of the above-ground vegetation's soil nitrogen requirement. This is expressed by both total and annual requirement per rotation and per total simulated time. Table XV also indicates the amount of nitrogen in the soil at the end of 360 years of forest management.

The effect of timber utilization standards is indicated in runs 1 and 2 where 60-year Douglas-fir rotations, slash removal

Figure 20. Simulated Forest Floor and Soil Nitrogen; Run 6: 60 yr. Douglas-fir rotation alternated with a 15 yr. alder rotation; whole tree harvesting; remove slash (4 = forest floor nitrogen (X4); S = soil nitrogen (X5)).

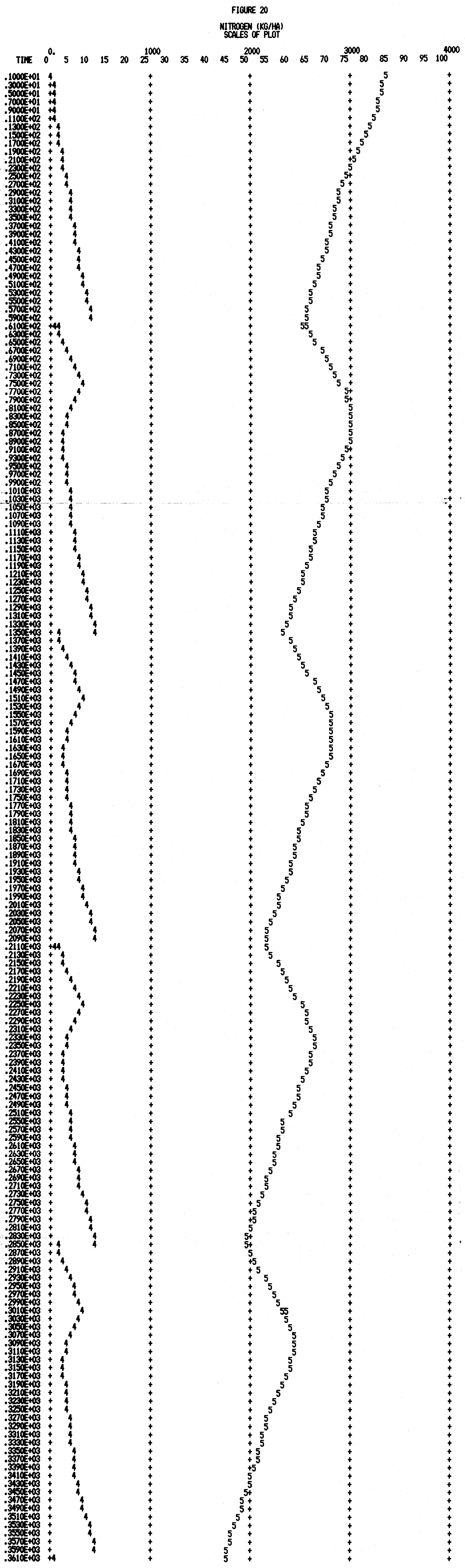


Figure 20. Simulated forest floor and soil nitrogen; Run 6.

TABLE XIV. SIMULATED FOREST FLOOR NITROGEN.

PRESCRIPTION **		FOREST FLOOR NITROGEN		
Run Number	Description	Average Total Accumulation per Rotation (kg/ha)	Average Annual Accumulation per Rotation (kg/ha/yr)	Total Accumulation at the End of 360 yrs. (kg/ha)
1	WT-UF-60-R	55	.9	55
2	BO-UF-60-R	287	4.8	287
3	WT-NF-60-R	46	.8	45
4	BO-NF-60-R	228	3.8	228
5	WT-NF-60-L	1029	17.2	1613
6	WT-15A-60-R	65	1.1	66
7	WT-40A-60-R	122	2.0	145
8	WT-UF-90-R	91	1.0	90
9	BO-UF-90-R	351	3.9	351
10	BO-NF-90-R	263	2.9	262
11	BO-NF-90-L	1472	16.4	2023
12	BO-NF-120-R	255	2.1	252
13	BO-NF-120-L	1266	10.5	1748
14	BO-UF-120-R	347	2.9	347
15	WT-NF-50-R	50	1.0	50 *

* Total simulated time was 350 years.

TABLE XIV. SIMULATED FOREST FLOOR NITROGEN. (CONT.)

TRANSFER OF NITROGEN FROM THE FOREST FLOOR TO THE SOIL				
Total Transfer per Rotation		Annual Transfer per Rotation		
First Rotation (kg/ha)	Last Rotation (kg/ha)	First Rotation (kg/ha)	Last Rotation (kg/ha)	Run Number
1719	1776	28.7	29.6	1
1719	2001	28.7	33.3	2
1527	1533	25.5	25.6	3
1524	1727	25.4	28.8	4
1527	1751	25.5	29.2	5
1527	1811	25.4	30.2	6
1527	1440	25.5	24.0	7
2442	2530	27.1	28.1	8
2442	2765	27.1	30.7	9
2255	2498	25.1	27.8	10
2255	2736	25.1	30.4	11
2975	3206	24.8	26.7	12
2975	3463	24.8	28.9	13
3162	3466	26.3	28.9	14
1266	1297	25.3	25.9	15

** The description consists of four codes, representing the utilization standard, fertilization practice, rotation length and slash treatment, in that order. The codes are as follows:

Utilization Standard - WT whole tree harvesting
BO bole only harvesting

Fertilization Practice - NF no fertilization
UF urea fertilization
15A 15 year alder rotations
40A 40 year alder rotations

Rotation Length - in years

Slash Treatment - R remove slash
L leave slash in place

TABLE XV. SIMULATED TOTAL SOIL NITROGEN.

Description	SOIL NITROGEN				
	Average Total Required Per Rotation (kg/ha)	Average Annual Required Per Rotation (kg/ha/yr)	Total Required for 360 yrs. (kg/ha)	Average Annual Required For 360 yrs. (kg/ha/yr)	Amount at the End of 360 yrs. ** (kg/ha)
1 WT-UF-60-R	755	12.6	4530	12.6	-1166
2 BO-UF-60-R	548	9.1	3288	9.1	76
3 WT-NF-60-R	830	13.8	4978	13.8	-1614
4 BO-NF-60-R	677	11.3	4064	11.3	- 700
5 WT-NF-60-L	673	11.2	4036	11.2	- 672
6 WT-15A-60-R	639	10.7	1611	4.5	1753
7 WT-40A-60-R	938	15.6	429	1.2	2935
8 WT-UF-90-R	893	9.9	3572	9.9	- 208
9 BO-UF-90-R	700	7.8	2798	7.8	566
10 BO-NF-90-R	817	9.1	3266	9.1	98
11 BO-NF-90-L	717	8.0	2869	8.0	495
12 BO-NF-120-R	710	5.9	2131	5.9	1233
13 BO-NF-120-L	739	6.2	2217	6.2	1147
14 BO-UF-120-R	596	5.0	1789	5.0	1575
15 WT-NF-50-R	712	14.2	4986 *	14.2 *	-1622 *

** Negative values indicate that requirement was in excess of the amount of nitrogen in the soil.

* Total simulated time was 350 years.

TABLE XV. SIMULATED TOTAL SOIL NITROGEN. (CONT.)

TIME WHEN SOIL NITROGEN BECAME ZERO (if applicable) (yrs)	Run Number
at time 263	1
-	2
at time 246	3
at time 296	4
at time 294	5
-	6
-	7
at time 326	8
-	9
-	10
-	11
-	12
-	13
-	14
at time 234	15

and urea fertilization are practiced. Although in both cases 90 percent of the slash was removed from the site, harvesting the boles only made a greater contribution to the 10 percent of the slash that remained and resulted in more nitrogen added to the soil in the next rotation. Table XIV shows that with whole tree harvesting the average forest floor nitrogen accumulation was only 55 kg/ha/rotation with 29.6 kg/ha annually transferred to the soil (Run 1). In comparison, harvesting the boles only (Run 2) resulted in an average accumulation of 287 kg/ha/rotation with 33.3 kg/ha/yr added to the soil. During whole tree harvesting, accelerated soil erosion and leaching losses combine with this slash effect to require more nitrogen from the soil during each rotation, 755 kg/ha, compared to 548 kg/ha with bole only harvesting (see Table XV). While the soil nitrogen variable decreased to zero in year 263 when whole trees were harvested, 76 kg/ha still remained in year 360 when only the boles were removed.

The absence of urea fertilization did not change the relative difference in the effects of the two utilization standards, as indicated by runs 3 and 4. However, the fertilizer addition moderated the effects of the greater soil nitrogen requirements made by whole tree harvesting. As shown in Table XV, in the absence of fertilization, the soil nitrogen requirement with bole only harvesting (Run 4) increased from 9.1 to 11.3 kg/ha/yr, a 24 percent increase. In contrast, the combination of whole tree harvesting and no fertilization (Run 3) resulted in only a 10 percent increase, from 12.6 to 13.8 kg/ha/yr. In summary, urea fertilization practices did not change the consistently greater soil nitrogen requirement of whole tree harvesting, 13.8 kg/ha/yr, relative to harvesting only the boles, 11.3 kg/ha/yr.

The combined effect of rotation length and utilization standard is indicated through comparisons between whole tree and bole only harvesting at both 60 (Runs 1 and 2) and 90-year rotations (Runs 8 and 9). Slash removal and urea fertilization are common to all four prescriptions. Even with the longer rotation length, harvesting whole trees (Run 8) consistently contributed to lower forest floor nitrogen accumulations, less forest floor nitrogen added to the soil and therefore, more removed from the soil compared to the harvesting of boles only (Run 9) (Tables XIV and XV). However, between rotation lengths, the 90-year one in conjunction with whole tree harvesting (Run 8) had less nitrogen transferred annually from the forest floor to the soil, 28.1 kg/ha/yr, than the 60-year whole tree harvesting prescription, 29.6 kg/ha/yr (Run 1). A similar trend was found with bole only harvesting at the two rotation lengths. Since the yearly forest floor to soil additions decreased in the older stands, the average rate calculated over the length of the rotation was lower in the 90-year stands. This trend did not contribute to similar differences in soil nitrogen requirements. Rather, with both bole only and whole tree harvesting, shorter rotations required more soil nitrogen annually than longer rotations (Table XV).

Another consideration is the effect of slash treatment on forest floor and soil nitrogen. This is indicated by a comparison of runs 3 and 5, which both had 60-year rotation lengths, whole tree utilization and no fertilizer additions. Slash removal (Run 3) resulted in less forest floor nitrogen added to the soil annually than when slash was left in place (Run 5) (Table XIV). Average soil nitrogen required per rotation increased from 673 kg/ha with slash left to 830 kg/ha when slash was removed (Table XV). These relative effects of slash removal did not change when the rotation was lengthened to 90 years and bole only harvesting practiced. Again, low accumulations of forest floor nitrogen with slash removal (Run 10) resulted in smaller additions to the soil compared to when slash was left in place (Run 11). Although the choice of bole only harvesting lessened the difference in soil nitrogen requirements, slash removal still resulted in higher requirements than when slash was left (Table XV).

In several cases, the simulated forest floor nitrogen accumulated to unrealistically high levels when slash was left in place, for example, 1472 kg/ha/rotation in run 11 (Table XIV). This probably does not reflect model inadequacies in representing decomposition, but rather the omission of a process such as fire. It is likely that in the real forest system, wildfires would occur to reduce forest floor accumulations. Despite this problem, the relative differences between slash treatments should still be consistently represented by the model.

The present model shows the same general trends in forest floor nitrogen as found by Aber, Botkin and Melillo (1978). In a model of forest floor dynamics in northeastern hardwood forests, Aber _et al_. simulated the effects of utilization standard, slash removal and rotation length on forest floor nitrogen availability. Their predicted increases in nitrogen availability the first 5 to 10 years after clearcutting were similar to my model's increase in the nitrogen transfer from the forest floor to the soil. Aber _et al_. also found that whole tree harvesting decreased the forest floor biomass and nitrogen availability, and when combined with slash removal and short rotations, further decreased the forest floor nitrogen. Although the two forest types differ, the present model shows the same trend.

Swank and Waide (1980; and Waide and Swank, 1977) present results of nitrogen simulations in oak-hickory and loblolly pine forests in southeastern United States. In both models, they found that bole only utilization standards resulted in an immediate increase in forest floor nitrogen after harvesting, followed by a rapid decrease as nitrogen was added to the soil. My model produced a similar effect. Swank and Waide also indicated that shorter rotations resulted in less nitrogen added to the forest floor and soil and significantly less nitrogen remaining in the soil after 360 simulated years. These were the same type of relationships found in the present model.

Kimmins, Scoullar and Feller (1980 (draft); and Kimmins, 1977) evaluated the effects of intensive management practices on growth and nitrogen cycling in Douglas-fir forests in western Canada. Their simulation results were of a qualitative nature, indicating a trend of increasing forest floor and soil nitrogen losses with complete tree utilization and with shortening of rotation lengths. The present model is in agreement with these trends.

Another management consideration is the effect of fertilization practices on forest floor and soil nitrogen. Four prescriptions were compared, all having 60-year rotations, whole tree harvesting and slash removal, but differing in their fertilizer options. In the absence of fertilization, the forest floor nitrogen accumulation averaged 46 kg/ha/rotation (Run 3). The addition of urea fertilizer increased the accumulation to 55 kg/ha (Run 1). A further gain was obtained when alder rotations were alternated with Douglas-fir rotations. In the case of 15-year alder rotations, forest floor nitrogen accumulation was 65 kg/ha/Douglas-fir rotation (Run 6), increasing to 122 kg/ha in the 40-year alder prescription (Run 7) (Table XIV). Forest floor nitrogen contributions to the soil followed the same progression, increasing with urea additions and alder rotations. This resulted in somewhat lower soil nitrogen requirements when urea was applied, and considerably lower if alder was part of the prescription. However, both the urea and no fertilization prescriptions caused the soil nitrogen variable to decrease to zero, while the 15 and 40-year alder prescriptions resulted in 1753 and 2935 kg/ha soil nitrogen, respectively, at the end of simulated time (Table XV). Therefore, urea fertilization alone is not adequate to prevent long-term soil nitrogen depletions.

Urea fertilization effects were also simulated in combination with bole only harvesting (Runs 2 and 4). Slash removal practices and 60-year rotation lengths were common to both prescriptions. Again, average forest floor nitrogen accumulation was higher and soil nitrogen requirement lower in the urea prescription (Run 2) compared to no fertilization (Run 4). But, the bole only utilization standard in combination with urea fertilization resulted in more forest floor nitrogen and lower soil nitrogen requirements than in whole tree harvesting.

Given the common assumptions of bole only harvesting, slash removal and urea fertilization, increasing the rotation length consistently lowered the average annual soil nitrogen requirement. An average of 9.1 kg/ha/yr with 60-year rotations (Run 2) decreased to 7.8 kg/ha/yr during the 90-year rotation (Run 9) and further decreased to 5.0 kg/ha/yr in the 120-year case (Run 14). In summary, the combination of such intensive practices as short rotation lengths, whole tree harvesting, slash removal and urea fertilization caused long-term depletion of nitrogen in the forest floor and soil.

2. Nitrogen in the Douglas-fir and Understory Vegetation

The trends in Douglas-fir and understory nitrogen are shown in Figure 21 for a prescription consisting of 120-year rotations with no fertilization practices (Run 13). The Douglas-fir components exhibit characteristic S-shaped curves of nitrogen accumulation over time. The understory nitrogen increased until the Douglas-fir began to fully occupy the site, and then decreased to very low levels. Figure 22 indicates the trends resulting from run 1, which had a 60-year rotation length with urea fertilization at age 36. Total foliage and branch nitrogen was substantially increased by the addition of fertilizer, with wood and bark nitrogen responding with a smaller increase. The understory contained only slightly more nitrogen due to the fertilization. The alternating of a 60-year Douglas-fir rotation with a 15-year alder one (Run 6) is shown in Figure 23. The effect of the alder is indicated by the increased nitrogen accumulations in the succeeding Douglas-fir rotation.

Table XVI summarizes the effects of the prescriptions on Douglas-fir wood and bark nitrogen. It includes both total and annual nitrogen accumulations over one rotation and over the total 360-year period. Table XVII presents similar results for the

Figure 21. Simulated Douglas-fir and Understory Nitrogen; Run 13: 120 yr. rotation; bole only harvesting; leave slash; no fertilization (1 = Douglas-fir wood and bark nitrogen (X1); 2 = Douglas-fir foliage and branch nitrogen (X2); 3 = understory nitrogen (X3)).

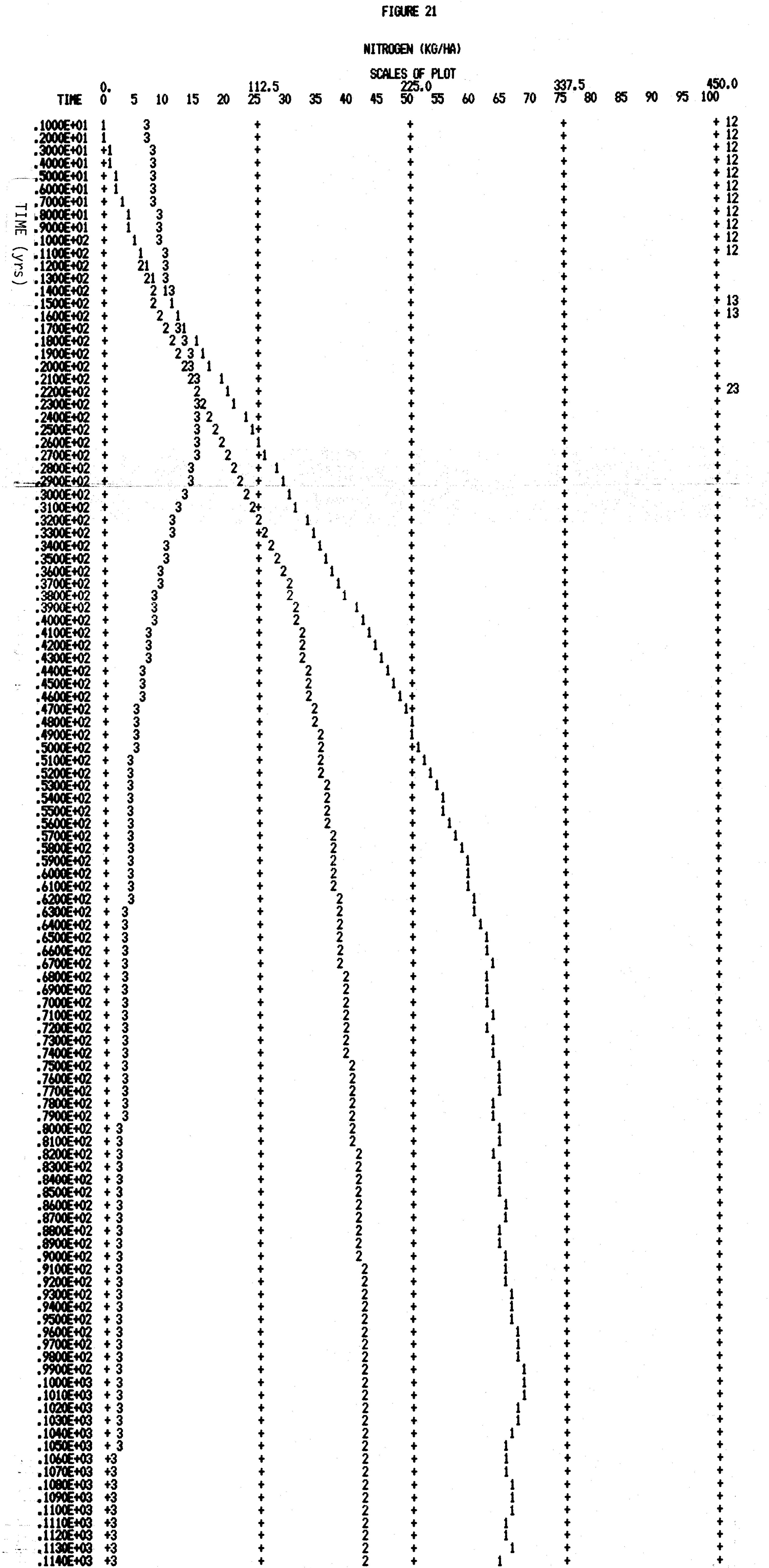


Figure 21. Simulated Douglas-fir and Understory nitrogen; Run 13.

Figure 22. Simulated Douglas-fir and Understory Nitrogen; Run 1: 60 yr. rotation; whole tree harvesting; remove slash; urea fertilization (1 = Douglas-fir wood and bark nitrogen (X1); 2 = Douglas-fir foliage and branch nitrogen (X2); 3 = understory nitrogen (X3)).

FIGURE 22

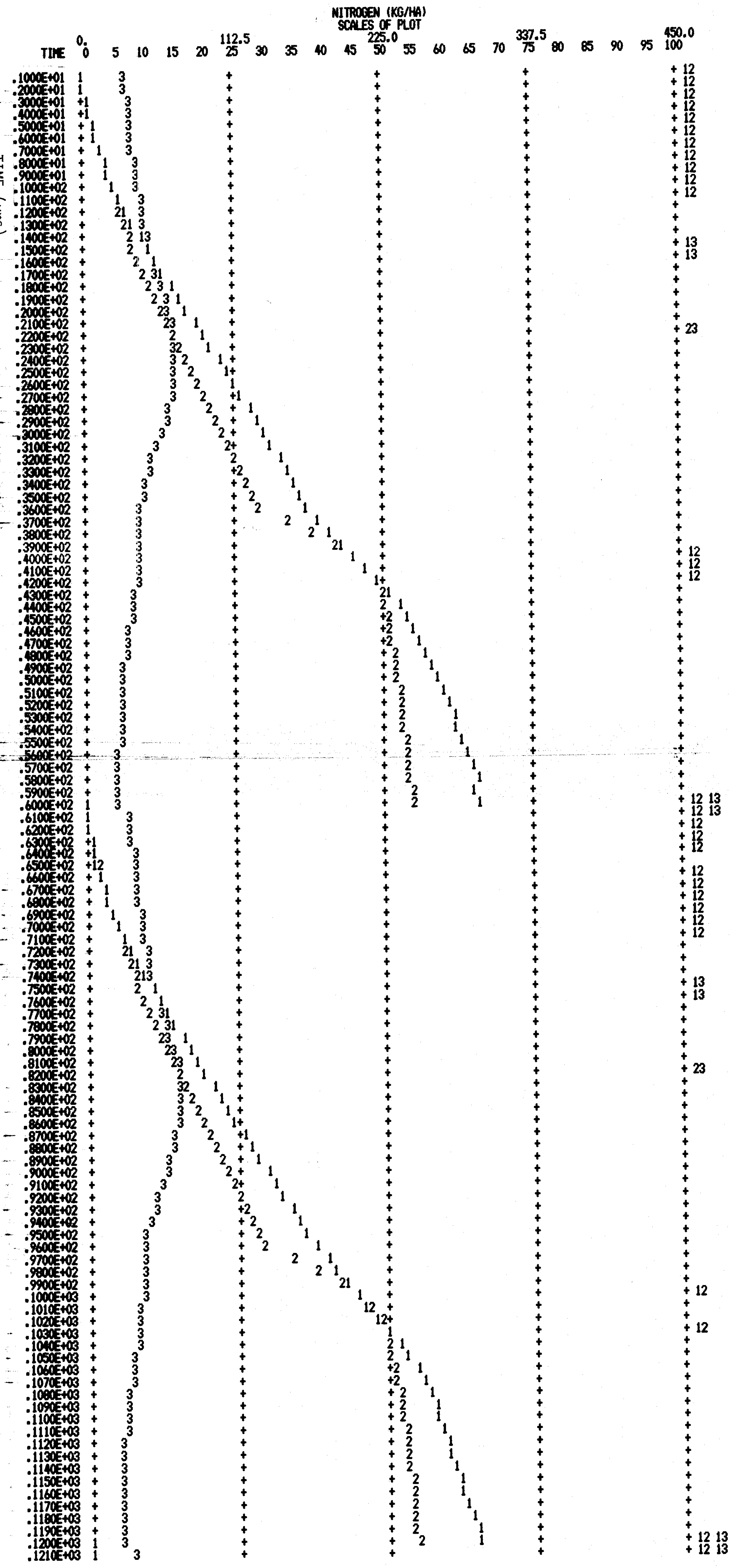


Figure 22. Simulated Dougals-fir and understory nitrogen; Run 1.

Figure 23. Simulated Douglas-fir and Understory Nitrogen; Run 6: 60 yr. Douglas-fir rotation alternated with a 15 yr. alder rotation; whole tree harvesting; remove slash (1 = Douglas-fir wood and bark nitrogen (X1); 2 = Douglas-fir foliage and branch nitrogen (X2); 3 = understory nitrogen (X3)).

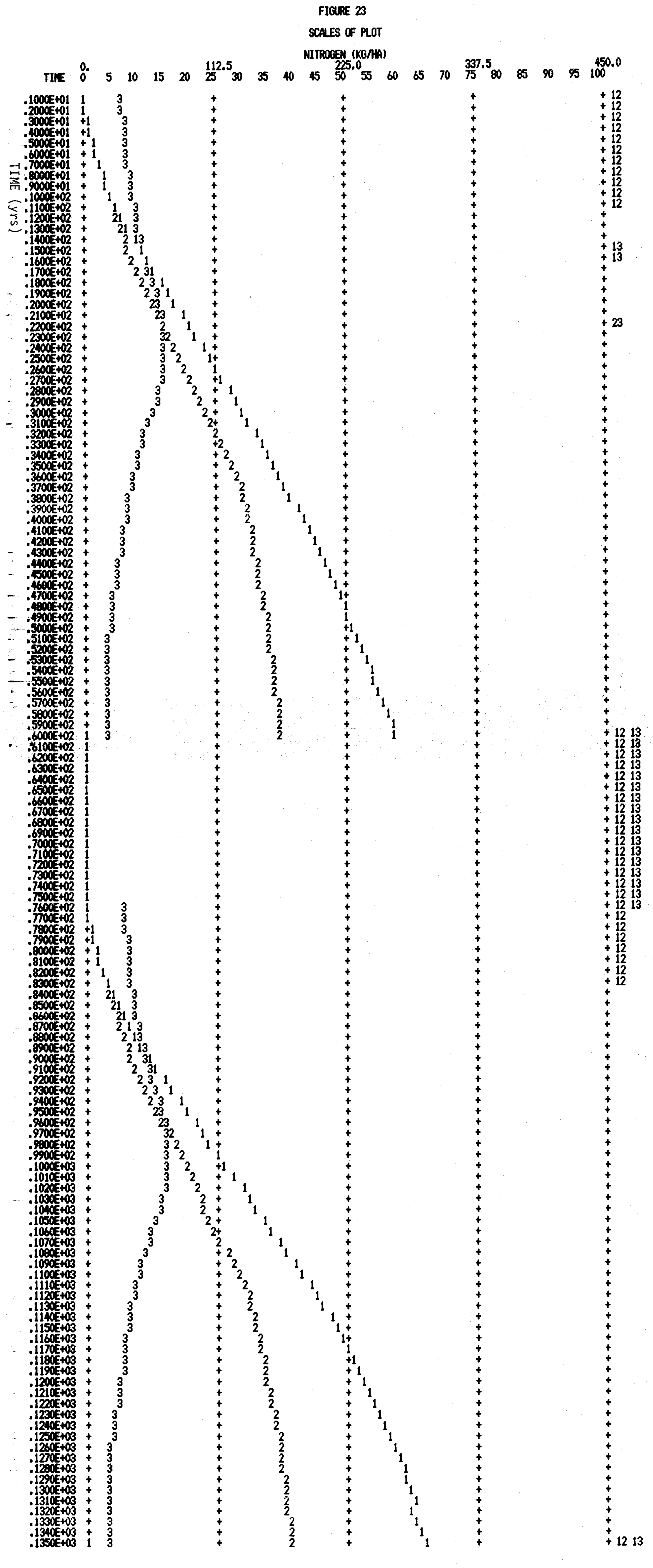


Figure 23. Simulated Douglas-fir and understory nitrogen; Run 6.

TABLE XVI. SIMULATED DOUGLAS-FIR WOOD AND BARK NITROGEN.

PRESCRIPTION		DOUGLAS-FIR WOOD AND BARK NITROGEN			
Run Number	Description	Total Accumulation per Rotation (kg/ha)	Annual Accumulation per Rotation (kg/ha/yr)	Total Accumulation in 360 yrs. (kg/ha)	Annual Accumulation in 360 yrs. (kg/ha/yr)
1	WT-UF-60-R	297	5.0	1785	5.0
2	BO-UF-60-R	297	5.0	1785	5.0
3	WT-NF-60-R	260	4.3	1557	4.3
4	BO-NF-60-R	260	4.3	1557	4.3
5	WT-NF-60-L	260	4.3	1557	4.3
6	WT-15A-60-R	288	4.8	1438	4.0
7	WT-40A-60-R	291	4.9	1164	3.2
8	WT-UF-90-R	331	3.7	1326	3.7
9	BO-UF-90-R	331	3.7	1326	3.7
10	BO-NF-90-R	295	3.3	1181	3.3
11	BO-NF-90-L	295	3.3	1181	3.3
12	BO-NF-120-R	292	2.4	877	2.4
13	BO-NF-120-L	292	2.4	877	2.4
14	BO-UF-120-R	324	2.7	973	2.7
15	WT-NF-50-R	230	4.6	1609 *	4.6 *

TABLE XVII. SIMULATED DOUGLAS-FIR FOLIAGE AND BRANCH NITROGEN.

PRESCRIPTION		DOUGLAS-FIR FOLIAGE AND BRANCH NITROGEN			
Run Number	Description	Total Accumulation per Rotation (kg/ha)	Annual Accumulation per Rotation (kg/ha/yr)	Total Accumulation in 360 yrs. (kg/ha)	Annual Accumulation in 360 yrs. (kg/ha/yr)
1	WT-UF-60-R	246	4.1	1476	4.1
2	BO-UF-60-R	246	4.1	1476	4.1
3	WT-NF-60-R	167	2.8	1003	2.8
4	BO-NF-60-R	167	2.8	1003	2.8
5	WT-NF-60-L	167	2.8	1003	2.8
6	WT-15A-60-R	175	2.9	875	2.4
7	WT-40A-60-R	176	2.9	705	2.0
8	WT-UF-90-R	265	2.9	1061	2.9
9	BO-UF-90-R	265	2.9	1061	2.9
10	BO-NF-90-R	186	2.1	746	2.1
11	BO-NF-90-L	186	2.1	746	2.1
12	BO-NF-120-R	188	1.6	564	1.6
13	BO-NF-120-L	188	1.6	564	1.6
14	BO-UF-120-R	267	2.2	801	2.2
15	WT-NF-50-R	157	3.1	1097 *	3.1 *

foliage and branch nitrogen, and Table XVIII, understory nitrogen.

Urea fertilization resulted in a 14 percent increase in total wood and bark nitrogen over a 60-year rotation, compared to 11 and 12 percent increases with 15 and 40-year alder rotations, respectively. Although the alder prescriptions resulted in lesser increases in nitrogen accumulation, this should be considered in relation to alder's effects in slowing long-term soil nitrogen depletion. When the rotation was lengthened to 120 years, the addition of urea fertilizer caused only an 11 percent increase in total wood and bark nitrogen.

Response to urea fertilization was greater in the foliage and branch nitrogen, ranging from 42 to 47 percent increases, since this component had a greater uptake rate than the wood and bark component. The alder prescriptions resulted in only a five percent increase in total Douglas-fir foliage and branch nitrogen accumulation per rotation. However, the alder effect was distributed over the entire rotation compared to the urea's 10-year response period.

3. Nitrogen Losses from Vegetation Removal and Slash Treatment

The nitrogen removed by timber harvesting and slash treatment is summarized by Table XIX. The results are expressed on both a rotation and 360-year basis. In all prescriptions where slash

TABLE XVIII. SIMULATED UNDERSTORY NITROGEN.

PRESCRIPTION		UNDERSTORY NITROGEN			
Run Number	Description	Total Accumulation per Rotation (kg/ha)	Annual Accumulation per Rotation (kg/ha/yr)	Total Accumulation in 360 yrs. (kg/ha)	Annual Accumulation in 360 yrs. (kg/ha/yr)
1	WT-UF-60-R	22.5	.38	135.0	.38
2	BO-UF-60-R	22.5	.38	135.0	.38
3	WT-NF-60-R	15.8	.26	94.7	.26
4	BO-NF-60-R	15.8	.26	94.7	.26
5	WT-NF-60-L	15.8	.26	94.7	.26
6	WT-15A-60-R	17.3	.29	86.3	.24
7	WT-40A-60-R	17.7	.29	70.7	.20
8	WT-UF-90-R	15.6	.17	62.3	.17
9	BO-UF-90-R	15.6	.17	62.3	.17
10	BO-NF-90-R	8.9	.10	35.5	.10
11	BO-NF-90-L	8.9	.10	35.5	.10
12	BO-NF-120-R	1.4	.01	4.1	.01
13	BO-NF-120-L	1.4	.01	4.1	.01
14	BO-UF-120-R	8.1	.07	24.2	.07
15	WT-NF-50-R	16.9	.34	118.3 *	.34 *

* Total simulated time was 350 years.

TABLE XIX. NITROGEN REMOVED BY HARVESTING AND SLASH TREATMENT.

PRESCRIPTION		AVERAGE NITROGEN REMOVED PER ROTATION			
		DOUGLAS-FIR			
Run Number	Description	Wood & Bark (kg/ha)	Foliage & Branches (kg/ha)	Understory (kg/ha)	Forest Floor (kg/ha)
1	WT-UF-60-R	297	221	20	411
2	BO-UF-60-R	280	0	20	422
3	WT-NF-60-R	260	150	14	384
4	BO-NF-60-R	244	0	14	389
5	WT-NF-60-L	260	150	0	0
6	WT-15A-60-R	288	157	16	407
7	WT-40A-60-R	291	159	16	924
8	WT-UF-90-R	332	239	14	565
9	BO-UF-90-R	312	0	14	582
10	BO-NF-90-R	277	0	8	523
11	BO-NF-90-L	277	0	0	0
12	BO-NF-120-R	275	0	1	460
13	BO-NF-120-L	275	0	0	0
14	BO-UF-120-R	305	0	7	537
15	WT-NF-50-R	230	141	18	291

TABLE XIX. NITROGEN REMOVED BY HARVESTING AND SLASH TREATMENT. (CONT.)

NITROGEN REMOVED OVER 360 YEAR PERIOD				
DOUGLAS-FIR				
Wood & Bark (kg/ha)	Foliage & Branches (kg/ha)	Understory (kg/ha)	Forest Floor (kg/ha)	Run Number
1784	1327	121	2465	1
1677	0	121	2533	2
1557	901	85	2304	3
1464	0	85	2334	4
1557	901	0	0	5
1439	787	79	2037	6
1164	634	63	3695	7
1326	956	57	2258	8
1246	0	57	2327	9
1109	0	33	2090	10
1109	0	0	0	11
825	0	4	1379	12
825	0	0	0	13
915	0	22	1611	14
1608 *	987 *	127 *	2039 *	15

* Total simulated time was 350 years.

removal was practiced, more nitrogen was taken out in the forest floor materials than in the Douglas-fir wood and bark. Foliage and branch nitrogen removed by whole tree harvesting represented 55 to 74 percent of the nitrogen removed in the wood and bark.

Penning De Vries et al. (1975), in their model of loblolly pine in the southeast, simulated annual nitrogen removal rates in the vegetation and forest floor. They predicted a low rate of 8.0 kg/ha/yr removed during a 40-year rotation with harvesting of boles and no forest floor burning, compared to a high rate of 26.7 kg/ha/yr with whole tree harvests and short, 25-year rotations. The relative differences in my model's simulated prescriptions agree with Penning De Vries et al.'s findings. The lowest rates of nitrogen removal in the present model, 2.3 kg/ha/yr, occurred with 120-year rotations, bole only harvesting and no slash removal (Run 13). Whole tree harvesting and shorter, 60-year rotations caused the removal rate to increase almost threefold to 6.8 kg/ha/yr (Run 5), which is consistent with the similar increase reported by Penning De Vries et al. They also found that fertilization with 200 kg/ha of nitrogen caused higher rates of nitrogen removal, 16.6 to 22.9 kg/ha/yr, than in the unfertilized treatments, 15.6 to 21.0 kg/ha/yr. The present model indicated a similar trend, with urea fertilization resulting in increased removal rates of 15.8 kg/ha/yr (Run 1) compared to 13.5 kg/ha/yr in the unfertilized prescription (Run 3).

4. Douglas-fir Timber Volumes

Figures 24, 25 and 26 show the trends in Douglas-fir biomass and timber volumes for the three prescriptions used as previous examples. The relative effects of fertilization practices on biomass and volume are the same as in the nitrogen accumulation curves.

The removal of wood, bark and branch volume and foliage biomass due to timber harvesting is summarized in Table XX. These values are based on the assumption that growth rates will be maintained over simulated time. The use of a 60-year rotations with urea fertilization and whole tree harvesting resulted in the greatest total wood and bark volume removed over the 360-year period (Run 1). A similar prescription with a bole only utilization standard produced 14 percent less Douglas-fir volume per rotation, but required 38 percent less soil nitrogen (Run 2) (Table XV). Lengthening the rotation resulted in less total Douglas-fir volume removed from the site, with similar trends in both the fertilized and unfertilized prescriptions.

Urea fertilization had the effect of increasing wood and bark volume by 15 percent, while the alder prescriptions resulted in 11 to 12 percent volume increases. However, the use of alder caused lower total Douglas-fir volumes over the simulated period, since the alder rotations were substituted for Douglas-fir production. Although the model does not predict alder volumes, alder

Figure 24. Simulated Douglas-fir Biomass (kg/ha) and Volume (m^3/ha); Run 13:

120 yr. rotation; bole only harvesting; leave slash; no fertilization (W = wood and bark biomass; B = branch biomass; F = foliage biomass; X = wood and bark volume; * = branch volume).

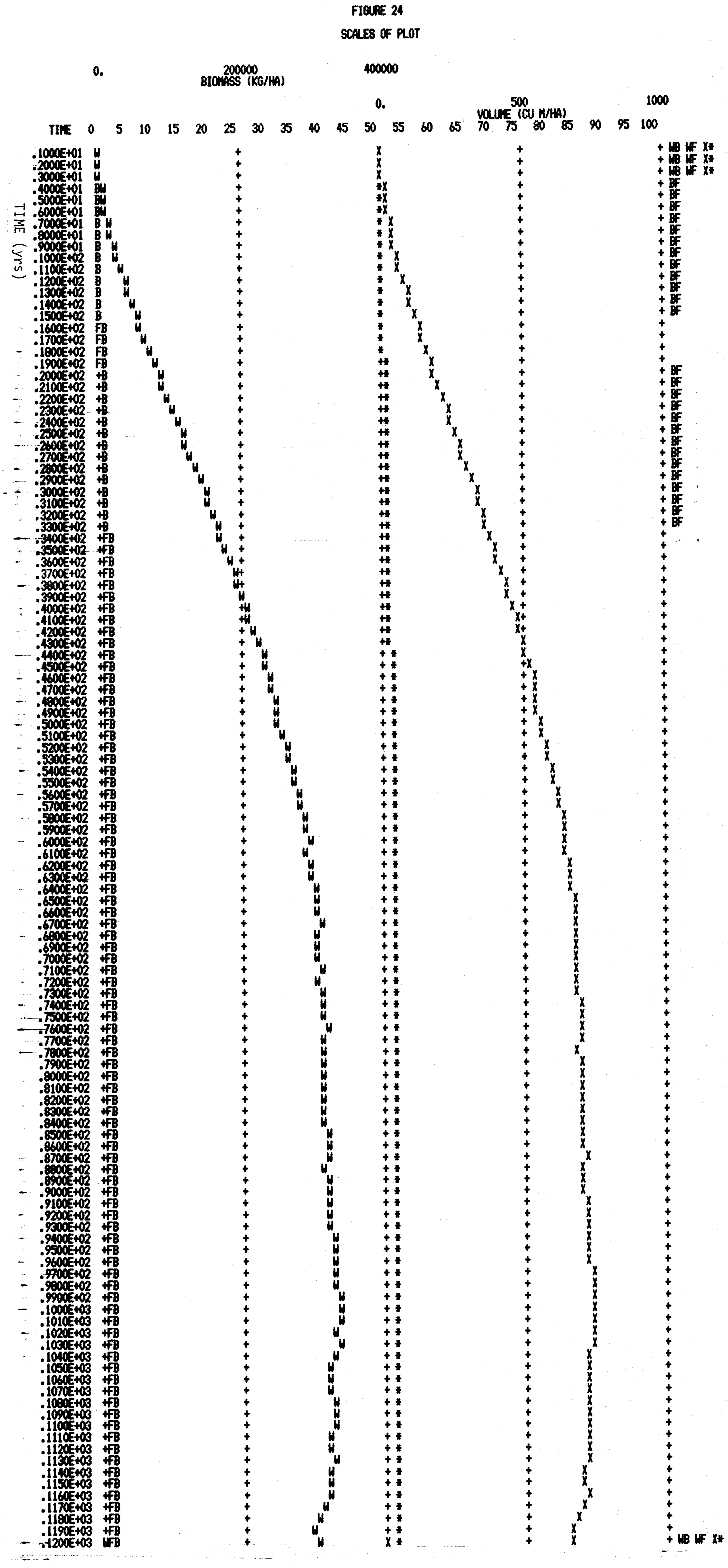


Figure 24. Simulated Douglas-fir biomass (kg/ha) and volume (cu m/ha); Run 13.

Figure 25. Simulated Douglas-fir Biomass (kg/ha) and Volume (m^3/ha); Run 1:

60 yr. rotation; whole tree harvesting; remove slash; urea fertilization (W = wood and bark biomass; B = branch biomass; F = foliage biomass; X = wood and bark volume; * = branch volume).

FIGURE 25

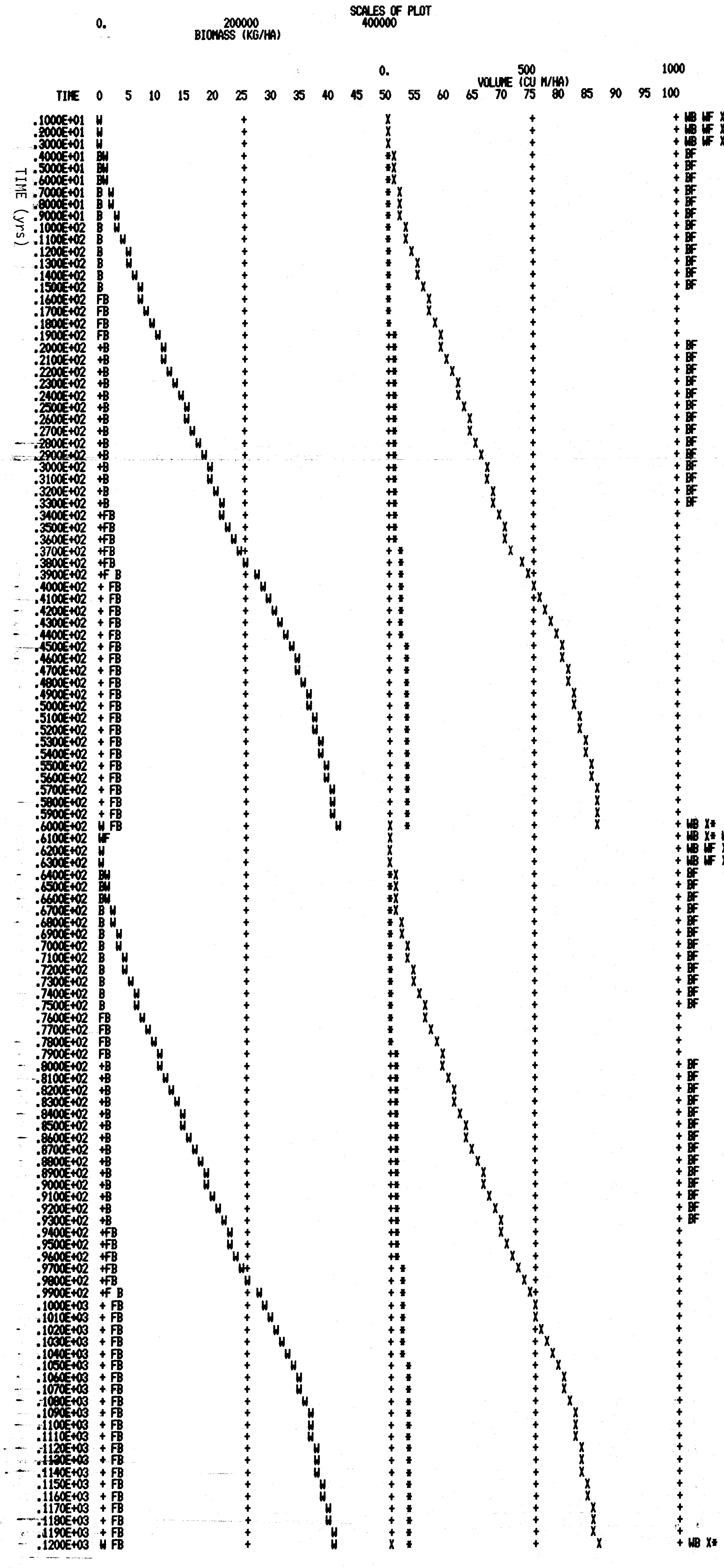


Figure 25. Simulated Douglas-fir biomass (kg/ha) and volume (cu m/ha); Run 1.

Figure 26. Simulated Douglas-fir Biomass (kg/ha) and Volume (m^3/ha); Run 6:

60 yr. Douglas-fir rotation alternated with a 15 yr. alder rotation; whole tree harvesting; remove slash (W = wood and bark biomass; B = branch biomass; F = foliage biomass; X = wood and bark volume; * = branch volume).

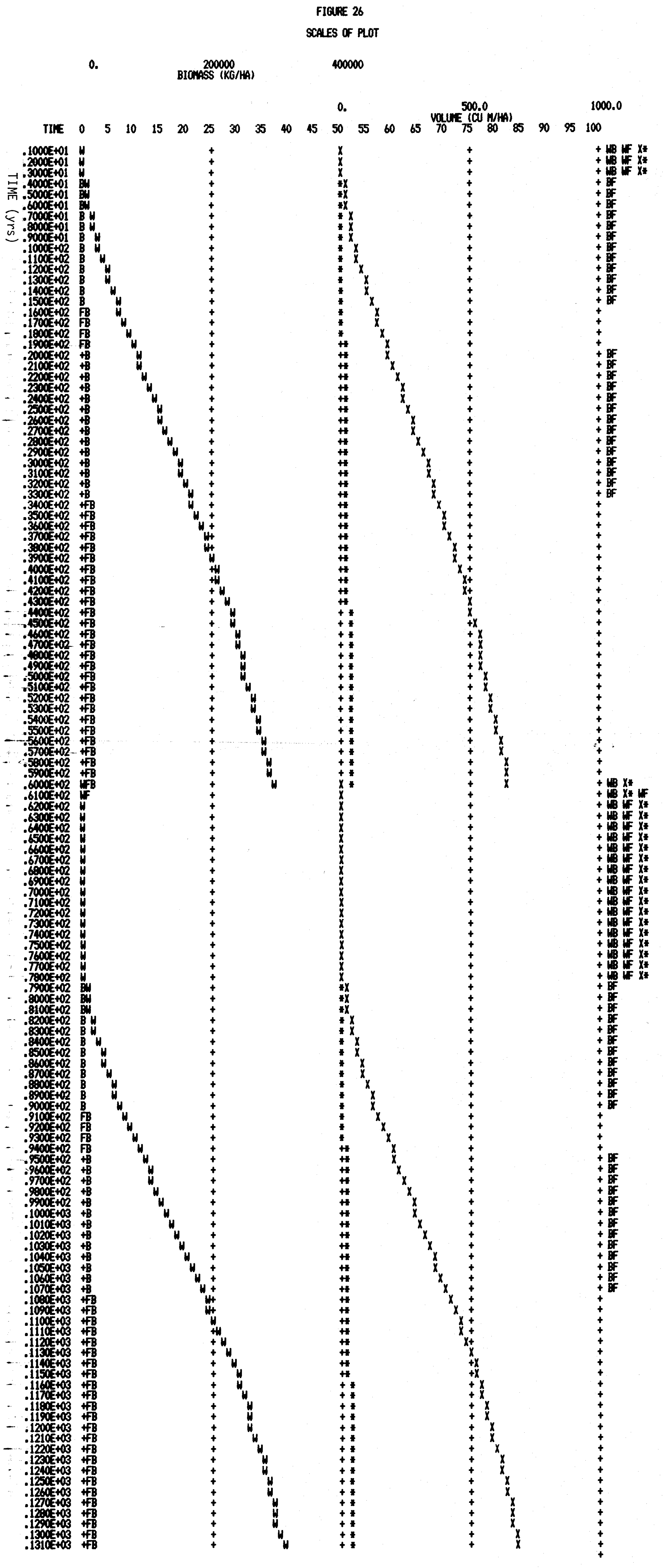


Figure 26. Simulated Douglas-fir biomass (kg/ha) and volume (cu m/ha); Run 6.

TABLE XX. DOUGLAS-FIR VOLUME AND BIOMASS REMOVED BY HARVESTING.

PRESCRIPTION		AVERAGE REMOVED PER ROTATION			TOTAL REMOVED OVER 360 YEAR PERIOD		
Run Number	Description	Wood & Bark Volume cu ft/ac	Branch Volume cu ft/ac	Foliage Biomass kg/ha	Wood & Bark Volume cu ft/ac	Branch Volume cu ft/ac	Foliage Biomass kg/ha
1	WT-UF-60-R	10345	716	12029	62071	4297	72176
2	BO-UF-60-R	9725	0	0	58348	0	0
3	WT-NF-60-R	9025	447	9543	54147	2683	57257
4	BO-NF-60-R	8483	0	0	50897	0	0
5	WT-NF-60-L	9025	447	9543	54147	2683	57257
6	WT-15A-60-R	10003	471	9863	50017	2356	49313
7	WT-40A-60-R	10124	476	9916	40496	1903	39662
8	WT-UF-90-R	11526	790	12347	46104	3161	49386
9	BO-UF-90-R	10835	0	0	43338	0	0
10	BO-NF-90-R	9652	0	0	38609	0	0
11	BO-NF-90-L	9652	0	0	38609	0	0
12	BO-NF-120-R	9553	0	0	28659	0	0
13	BO-NF-120-L	9553	0	0	28659	0	0
14	BO-UF-120-R	10599	0	0	31798	0	0
15	WT-NF-50-R	7993	415	9084	55950 *	2907 *	63585 *

* Total simulated time was 350 years.

pulpwood and sawlogs would be produced by the 15 and 40-year alder rotations, respectively. Douglas-fir grown after an alder rotation required only 10 to 36 percent of the soil nitrogen required by urea fertilized Douglas-fir (Table XV).

A last consideration is the prescription consisting of a 50-year rotation length, whole tree utilization, slash removal and no fertilization (Run 15). This prescription resulted in more total wood and bark volume in 350 years, 55,950 cu ft/ac, than a comparable 60-year rotation one produced in 360 years, 54,147 cu ft/ac (Run 3) (Table XX). The 50-year rotation length also resulted in the greatest average annual soil nitrogen requirement.

Aber _et al_. (1979) simulated the effects of utilization standards and slash removal on total yield of northeastern hardwood forests over a 90-year period. They found greater yields were produced by a 90-year rotation with whole tree harvesting and slash removal compared to a similar treatment with shorter, 30-year rotations. In contrast, a comparable set of runs for the present model shows that several shorter, 60-year rotations (Run 1) produced greater Douglas-fir yields than with longer, 90-year rotations (Run 8). This difference in the two models' results is due to Aber _et al_.'s built-in growth declines as soil nitrogen is depleted by shorter rotation harvesting regimes.

Kimmins, Scoullar and Feller (1980, draft) indicated that whole tree harvests in western Canadian Douglas-fir forests increased the total biomass removed but decreased the average annual biomass yield compared to harvesting boles only. My model predicts that both total and average annual volume yields are increased by whole tree harvesting. Again, this is due to Kimmins _et al_.'s assumption of growth declines in successive rotations.

5. The Difference in Nitrogen Additions to and Losses from the Ecosystem

Nitrogen additions occur through precipitation, fixation and fertilization, while losses take place from leaching, erosion, denitrification, volatilization and harvesting. The net difference, D, is represented by:

$$D = F0,4 + F0,5 - F1,0 - F2,0 - F3,0 - F4,0 - F5,0$$

Graphs of D indicate a net loss in the young stand, changing to a net gain as the stand ages. Figure 27 shows the results of a 120-year rotation with bole only harvesting, slash left in place and no fertilization (Run 13). Harvesting caused a large net loss in nitrogen (beyond the graph's scales) due to the Douglas-fir removal from the site. Increased soil erosion and nitrogen leaching after clearcutting also resulted in net losses of nitrogen from the ecosystem.

As indicated in Figure 28, the combination of urea fertilization, whole tree harvesting, slash removal and 60-year rotations

Figure 27. Simulated Difference in Nitrogen Additions and Losses (D);
Run 13:
120 yr. rotation; bole only harvesting; leave slash;
no fertilization (units are in kg/ha/yr).

FIGURE 27

DIFFERENCE IN NITROGEN ADDITIONS AND LOSSES FROM THE ECOSYSTEM

SCALES OF PLOT

(KG/HA/YR)

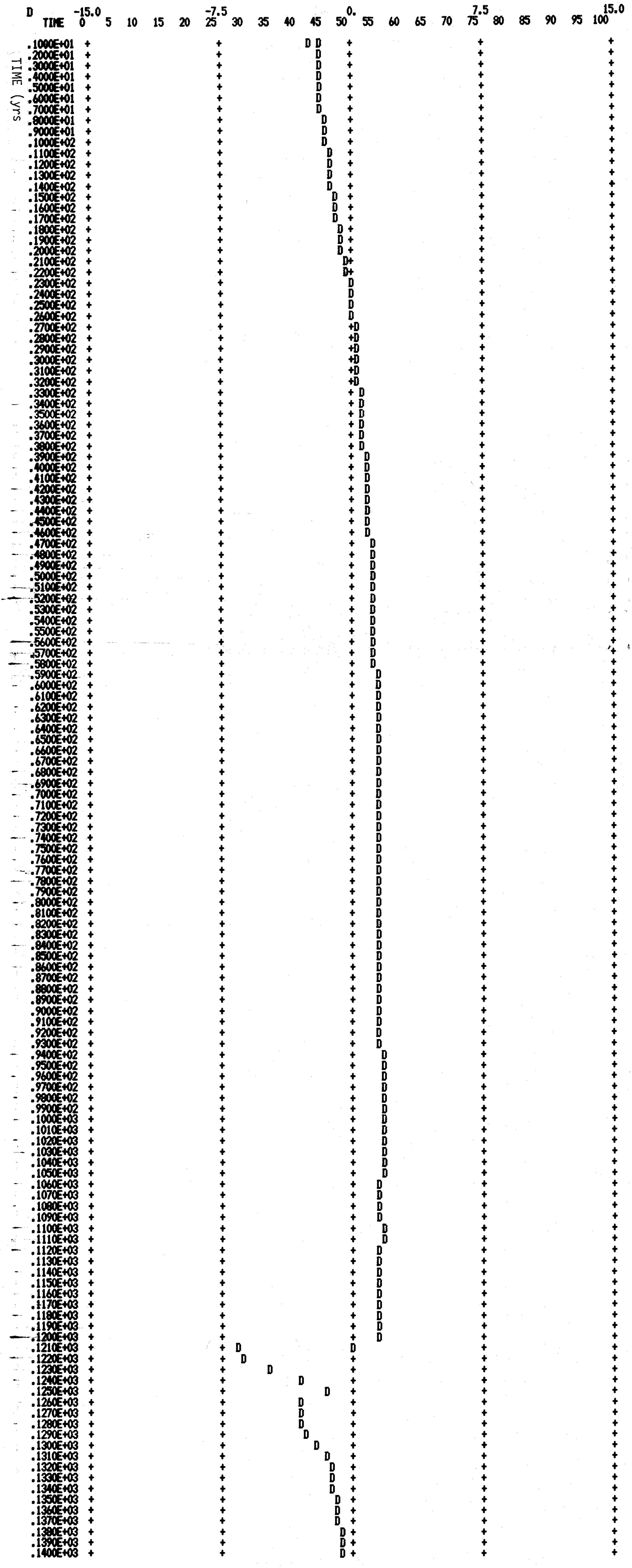


Figure 27. Simulated difference in nitrogen additions and losses (D); Run 13.

Figure 28. Simulated Difference in Nitrogen Additions and Losses (D); Run 1:

60 yr. rotation; whole tree harvesting; remove slash; urea fertilization (units are in kg/ha/yr).

FIGURE 28

DIFFERENCE IN NITROGEN ADDITIONS AND LOSSES FROM THE ECOSYSTEM

SCALES OF PLOT

(KG/HA/YR)

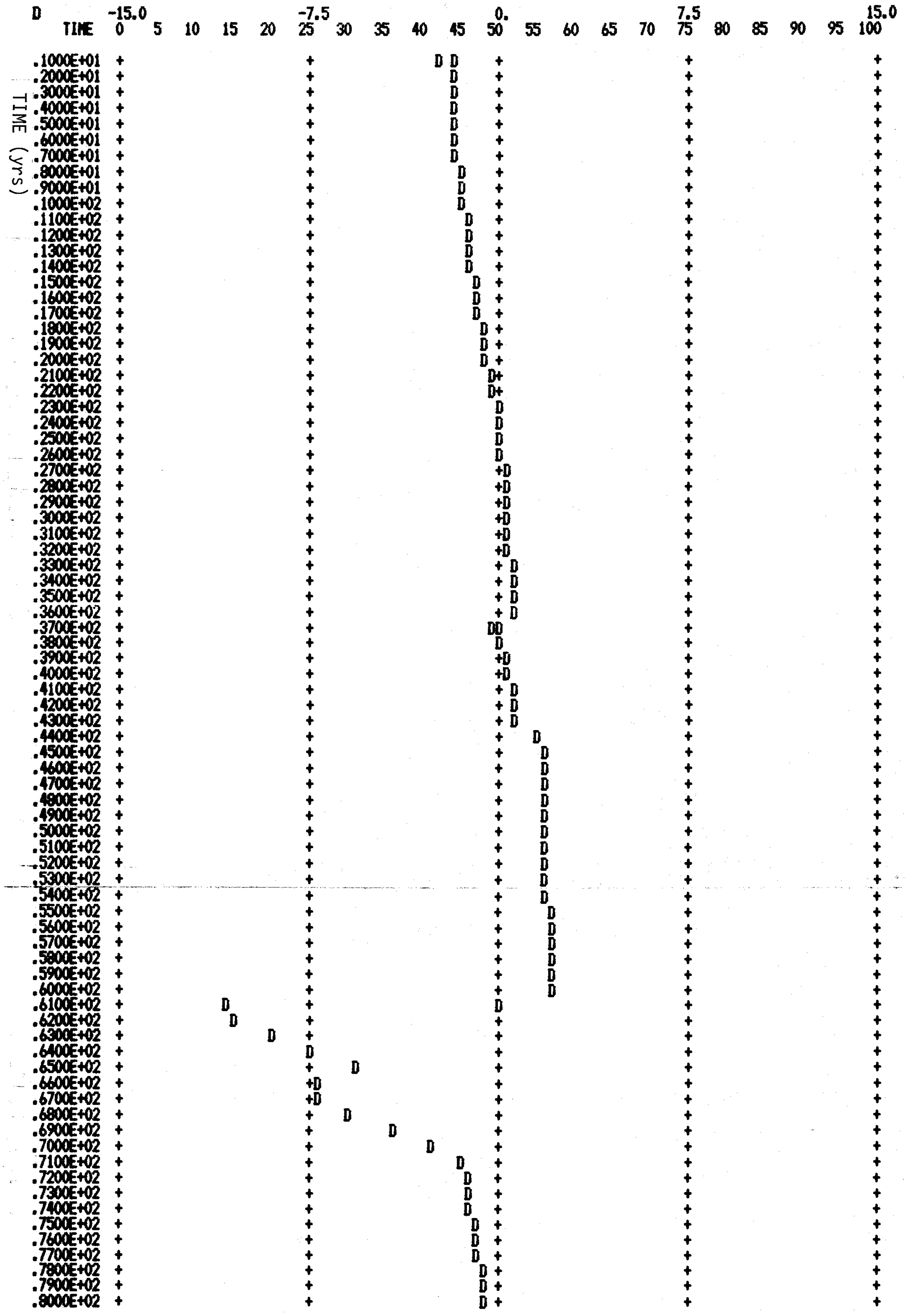


Figure 28. Simulated difference in nitrogen additions and losses(D); Run 1.

(Run 1) produced a greater net nitrogen loss after harvesting than in run 13. Although there is a large net gain at the time of fertilization, this does not have any long-term effects on reducing nitrogen losses.

Differences in nitrogen additions to and losses from the ecosystem are summarized in Table XXI. Whole tree utilization with 60-year rotations, urea fertilization and slash removal (Run 1) resulted in a net difference in nitrogen additions and losses of -13.0 kg/ha/yra. Harvesting boles only caused a smaller loss of -8.8 kg/ha/yr (Run 2). This is consistent with Swank and Waide's (1980, draft) reported increases in net nitrogen losses from -4.3 kg/ha/yr with bole only harvesting to almost double, -7.0 kg/ha/yr, with harvesting whole trees in southeastern oak-hickory forests.

Slash removal or burning practices resulted in a net nitrogen loss of double that found when slash was left in place (compare Runs 3 and 5). Other practices being equal, the longer 90-year rotations (Run 8) resulted in smaller net annual losses of nitrogen compared to the shorter, 60-year rotation (Run 1). This is also in agreement with Swank and Waide's findings (1980).
The greatest net annual loss, -14.8 kg/ha/yr, was caused by the 50-year rotation which utilized whole trees and removed the slash. The smallest loss occurred when 40-year alder rotations were alternated with Douglas-fir. It is significant that all the

TABLE XXI. THE DIFFERENCE IN NITROGEN ADDITIONS TO AND LOSSES FROM THE ECOSYSTEM.

PRESCRIPTION CODE		NET DIFFERENCE IN NITROGEN ADDITIONS & LOSSES			
Run Number	Description	Net Over Douglas-fir Rotation (kg/ha)	Range (kg/ha/yr)	Net Over 360 Years (kg/ha)	Net Annual Difference (kg/ha/yr)
1	WT-UF-60-R	-778	-954 to 210	-4670	-13.0
2	BO-UF-60-R	- 53	-727 to 210	-3181	- 8.8
3	WT-NF-60-R	-855	-813 to 1.4	-5130	-14.3
4	BO-NF-60-R	-674	-651 to 1.4	-4043	-11.2
5	WT-NF-60-L	-437	-418 to 1.4	-2621	- 7.3
6	WT-15A-60-R	***	-883 to 41	-1727	- 4.8
7	WT-40A-60-R	***	-1606 to 42	-436	- 1.2
8	WT-UF-90-R	-909	-1154 to 210	-3634	-10.1
9	BO-UF-90-R	-648	-916 to 210	-2593	- 7.2
10	BO-NF-90-R	-788	-814 to 1.7	-3150	- 8.8
11	BO-NF-90-L	-247	-283 to 1.7	- 989	- 2.7
12	BO-NF-120-R	-664	-738 to 1.8	-1991	- 5.5
13	BO-NF-120-L	-146	-289 to 1.8	- 582	- 1.6
14	BO-UF-120-R	-519	-858 to 210	-1558	- 4.3
15	WT-NF-50-R	-740 *	-684 to 1.1	-5178 *	-14.8 *

* Total simulated time is 350 years.

*** Not applicable.

simulated prescriptions resulted in net annual nitrogen losses. This will be considered further in the discussion of management implications.

IV. CONCLUSIONS

A. Management Implications

The results of this research indicate that we as forest managers can no longer make the unqualified assumption that growth rates will be maintained or increased as management intensity increases. The negative levels of soil nitrogen shown by the model imply that the assumed growth rates would not be maintained on these sites.

Shumway and Atkinson (1977) estimated Douglas-fir fertilization response by a relationship between soil nitrogen and relative increase in diameter growth. Assuming that this relationship holds for nitrogen losses as well as additions, a 2500 kg/ha difference in total soil nitrogen would roughly correspond to a 10 percent decrease in diameter growth. This is based on the assumption of .18 percent total nitrogen in these soils (from Cole and Gessel, 1968) and an initial soil nitrogen content of 3364 kg/ha. A 10 percent diameter growth decrease is assumed to represent about a 20 percent decrease in volume growth, based on relationships developed from site IV data in McArdle *et al*. (1961). Therefore, a prescription requiring approximately 2500 kg/ha total soil nitrogen over the first rotation would probably show at least a 20 percent volume decline in the next rotation. Since many of the simulated prescriptions resulted in much lower soil nitrogen levels at the end of 360 years, growth declines are likely to be even more severe.

Differences in the simulated prescriptions indicated that bole only harvesting resulted in lower soil nitrogen requirements than whole tree harvesting, even when slash removal was practiced. Also, increasing the rotation length decreased the soil nitrogen requirement. Therefore, effects of whole tree harvesting may be somewhat moderated by the use of longer rotations. Slash removal practices had the effect of increasing the rate of soil nitrogen depletion by the next stand. Management alternatives that consider leaving some of the slash or using only very low intensity slash burns may help to offset this loss.

Although urea fertilization initially increased growth, the nitrogen additions were not adequate to prevent future soil nitrogen depletions. However, the use of alder rotations greatly reduced the long-term rate of soil nitrogen decline. Through continuous additions over a period of time, the alder resulted in a nitrogen accumulation that was available throughout the next Douglas-fir rotation. In contrast, a one-time application of urea fertilizer resulted in a pulse addition of nitrogen, with a short growth response period and a return to conditions of net nitrogen losses. Consideration should be given to the use of smaller, more frequent additions of nitrogen fertilizer as a potential way of increasing growth while preventing long-term depletion of soil nitrogen.

The interplanting of Douglas-fir stands with nitrogen-fixing species such as alder is another possible way to add nitrogen to the site. This alternative would provide a continuously available source of nitrogen during the development of the Douglas-fir stand. Although it would reduce the number of Douglas-fir trees produced per unit area, interplanting with alder may have additional benefits of breaking up Douglas-fir monocultures and potentially reducing the probability of insect and disease epidemics. These effects, along with the increased diversity of the vegetation and wildlife, could also contribute to the maintenance of long-term forest productivity.

When comparing fertilization alternatives, economic considerations also need to be taken into account. Miller and Murray (1979) indicated that some red alder management alternatives may compare economically with urea nitrogen additions. Changing energy costs and markets for alder will affect such an analysis. When future soil nitrogen depletions and resulting long-term growth declines are entered into the economic analysis, the use of nitrogen-fixing species may become preferable to urea fertilization.

Interpretations of model results must be kept within the context of the model's limitations. A management prescription's effect on long-term productivity reflects each of the assumptions used to develop the nitrogen dynamics of the ecosystem. This is especially important relative to the components below-ground. The role of roots and mycorrhizae in forest nutrient cycling is under increasingly intensive study (Fogel, 1980 (in press); Santantonio, Hermann and Overton, 1977; Santantonio, 1974). Whether eventual inclusion of these components in a similar model would change the relative effects of management prescriptions cannot be determined at this time.

B. Direction for Future Research

The modeling effort has identified some data weaknesses in addressing questions of long-term forest productivity. The processes of nitrogen fixation, denitrification, decomposition, uptake and root-mycorrhizae interactions are five such areas. The magnitude of these nitrogen transfers, their behavior over time and response to management are all critical research needs. Since available soil nitrogen is such a small component of total soil nitrogen, it is essential that we better understand and quantify the relationship between the two.

The efficiency of alder nitrogen additions compared to fertilizer nitrogen is another area that needs to be explored. Nutrient losses by slash treatment, soil erosion and leaching are also poorly quantified at present, and the impacts of such losses over long time periods should be examined.

As management practices intensify on forest lands, increasing emphasis will be placed on nutrient management as an integral part of forest management. This will result in a continuing need for ecosystem modeling in an interdisciplinary framework. The long-term productivity of forests depends on more than just nitrogen cycling. It is also reflected in the interactions with other nutrients and effects of management practices on soil compaction, soil organic matter, diversity of plant and animal species and communities, fish and wildlife and insect populations, water quality, water yield and economic and social factors. The concept of "ecosystem" modeling will no longer be constrained to biological and physical aspects of forests, but will be expanded to encompass social and economic systems. The usefulness of future long-term productivity research to forest land managers and decision makers will be evaluated in this context.

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APPENDIX

```
      PROGRAM MAIN(INPUT,OUTPUT=64,TAPE5,TAPE6,TAPE1,TAPE2,
     1  TAPE3,TAPE4,TAPE7,TAPE8,TAPE9,TAPE10,TAPE11,TAPE12,
     2  TAPE13)
C
C**NITROGEN SIMULATION MODEL
C  TAPE 5 IS FOR INPUT DATA
C  TAPES 6 AND 11 ARE FOR OUTPUT
C
      DIMENSION NSET(5000)
      COMMON QSET(5000)
      COMMON /GCOM1/ ATRIB(25),JEVNT,MFA,MFE(100),MLE(100),MSTOP,NCRDR,N
     1NAPO,NNAPT,NNATR,NNFIL,NNQ(100),NNTRY,NPRNT,PPARM(50,4),TNOW,TTBEG
     2,TTCLR,TTFIN,TTRIB(25),TTSET
      COMMON /GCOM2/ DD(100),DDL(100),DTFUL,DTNOW,ISEES,LFLAG(50),NFLAG,
     2NNEQD,NNEQS,NNEQT,SS(100),SSL(100),TTNEX
      COMMON/UCOM1/TLASTH,G12(7),G1,G2,G3,G4,G5,PROP(5),G6(41),
     1  G7(41),G8,G9,G10(61),G11(61),PRN,G13(49),G14,REMAIN,SLASHN
      COMMON/UCOM2/AGE,IJK
      COMMON/UCOM3/XF04,XF05,XF10,XF14,XF20,XF24,XF30,XF34,XF40,XF45,
     1  XF50,XF51,XF52,XF53,XF60,XF70,XWBVOL,XBRVOL,FOLBIO,WBBIO,BRBIO
      COMMON/UCOM4/INOUT,UPTAKE,LITTERF
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
      COMMON/UCOM6/SF10(10),SF20(10),SF30(10),SF40(10),SF60(10),
     1  SF70(10),STIME(10),SFOLBIO(10)
      REAL LITTERF,INOUT
      EQUIVALENCE(NSET(1),QSET(1))
C
C**INITIALIZE CARD READER VALUE (NCRDR) AND PRINTER VALUE (NPRNT)
C
      NCRDR=5
      NPRNT=6
C
C**WRITE HEADINGS ON TAPE 11 AND TAPE 6
C
      WRITE(11,101)
101   FORMAT(*1TIME   SLASHN   REMAIN   KOUNT*)
      WRITE(6,104)
104   FORMAT(*0*,/,*T*,//////,* USER ECHO CHECK*,///)
C
C**READ IN VALUES OF THE STEM LITTERFALL TABLE (G12(I)); READ IN VALUES
C  FOR THE PROPORTIONATE INCREASE IN SOIL NITROGEN LEACHING LOSS AFTER
C  HARVESTING (PROP(I)); READ IN VALUES OF UNDERSTORY UPTAKE TABLE (G6(I)),
C  UNDERSTORY LITTERFALL TABLE (G7(I)) AND FOLIAGE AND BRANCH LITTERFALL
C  TABLE (G10(I)); READ IN VALUES OF THE DOUGLAS-FIR FOLIAGE AND BRANCH
C  UPTAKE TABLE (G11(I)) AND VALUES OF THE RATE OF NITROGEN TRANSFER
C  FROM THE FOREST FLOOR TO THE SOIL (G13(I))
C
      READ(5,102)(G12(I),I=1,7)
```

```
102   FORMAT(7(F6.1,2X))
      READ(5,103)(PROP(I),I=1,5)
103   FORMAT(5(F6.2,2X))
      READ(5,110)(G6(I),I=1,41)
110   FORMAT(3(12(F4.1,2X),/),5(F4.1,2X))
      READ(5,110)(G7(I),I=1,41)
      READ(5,111)(G10(I),I=1,61)
111   FORMAT(5(12(F4.1,2X),/),F4.1)
      READ(5,111)(G11(I),I=1,61)
      READ(5,112)(G13(I),I=1,49)
112   FORMAT(4(12(F4.1,2X),/),F4.1)
      WRITE(6,105)(PROP(I),I=1,5)
105   FORMAT(* PROP(I)  *,5(F6.2,2X),/)
      WRITE(6,106)(G12(I),I=1,7)
106   FORMAT(* G12*,2X,7(F6.1,2X),/)
      WRITE(6,107)(G6(I),I=1,41)
107   FORMAT(* G6  *,3(12(F4.1,2X),/,* *),5(F4.1,2X),/)
      WRITE(6,108)(G7(I),I=1,41)
108   FORMAT(* G7  *,3(12(F4.1,2X),/,* *),5(F4.1,2X),/)
      WRITE(6,109)(G10(I),I=1,61)
109   FORMAT(* G10 *,5(12(F4.1,2X),/,* *),F4.1,/)
      WRITE(6,121)(G11(I),I=1,61)
121   FORMAT(* G11 *,5(12(F4.1,2X),/,* *),F4.1,/)
      WRITE(6,122)(G13(I),I=1,49)
122   FORMAT(* G13 *,4(12(F4.1,2X),/,* *),F4.1,/)
C
C**CALL GASP EXECUTIVE
C
      CALL GASPF
C
      STOP
      END
```

```
      SUBROUTINE INTLC
      COMMON /GCOM1/ ATRIB(25),JEVNT,MFA,MFE(100),MLE(100),MSTOP,NCRDR,N
     1NAPO,NNAPT,NNATR,NNFIL,NNQ(100),NNTRY,NPRNT,PPARM(50,4),TNOW,TTBEG
     2,TTCLR,TTFIN,TTRIB(25),TTSET
      COMMON /GCOM2/ DD(100),DDL(100),DTFUL,DTNOW,ISEES,LFLAG(50),NFLAG,
     2NNEQD,NNEQS,NNEQT,SS(100),SSL(100),TTNEX
      COMMON/UCOM1/TLASTH,G12(7),G1,G2,G3,G4,G5,PROP(5),G6(41),
     1  G7(41),G8,G9,G10(61),G11(61),PRN,G13(49),G14,REMAIN,SLASHN
      COMMON/UCOM2/AGE,IJK
      COMMON/UCOM3/XF04,XF05,XF10,XF14,XF20,XF24,XF30,XF34,XF40,XF45,
     1  XF50,XF51,XF52,XF53,XF60,XF70,XWBVOL,XBRVOL,FOLBIO,WBBIO,BRBIO
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**READ IN PARAMETERS
C
      READ(5,102)(B1(I),I=1,2),(B2(I),I=1,2),(B3(I),I=1,2)
102   FORMAT(2(2(F6.3,2X),/),2(F6.3,2X))
      WRITE(6,103)(B1(I),I=1,2),(B2(I),I=1,2),(B3(I),I=1,2)
103   FORMAT(* *,///,T5,*  15 YR   40 YR*,//,* B1  *,2(F6.3,2X),
     1  //,* B2  *,2(F6.3,2X),//,* B3  *,2(F6.3,2X))
C
C**READ IN POLICY VARIABLES
C
      READ(5,113)RL,US,ST,JF,ARL
113   FORMAT(3(F5.1,2X),I5,2X,F5.1)
C
C**READ IN THE NET ANNUAL INCREMENTS OF NITROGEN ADDED TO THE SOIL
C  AND FOREST FLOOR BY A RED ALDER ROTATION
C
      READ(5,112)ALDERN,ALDERF
112   FORMAT(2(F5.1,2X))
      WRITE(6,114)RL
114   FORMAT(* *,////,* POLICY VARIABLES*,//,* DOUGLAS-FIR ROTATION LENG
     1TH IS  *,F5.1,*  YEARS*)
C
      IF(US.LE.0.0)GO TO 10
      WRITE(6,115)
115   FORMAT(* *,//,* WHOLE TREE HARVESTING (EXCLUDING ROOTS)*)
      GO TO 20
10    WRITE(6,116)
116   FORMAT(* *,//,* BOLE ONLY HARVESTING*)
C
20    IF(ST.LE.0.0)GO TO 30
      WRITE(6,117)
117   FORMAT(* *,//,* REMOVE SLASH*)
      GO TO 40
30    WRITE(6,118)
118   FORMAT(* *,//,* LEAVE SLASH IN PLACE*)
```

```
C
40    IF(JF.EQ.0)GO TO 50
      IF(JF.EQ.1)GO TO 60
      WRITE(6,119)
119   FORMAT(* *,//,* ALTERNATE DOUGLAS-FIR ROTATIONS WITH RED ALDER ROT
     1ATIONS*)
      WRITE(6,121)ARL
121   FORMAT(*0RED ALDER ROTATION LENGTH IS  *,F5.1,*  YEARS*)
      WRITE(6,122)ALDERN
122   FORMAT(*0ASSUME THE NET ANNUAL INCREMENT OF NITROGEN ADDED TO*,
     1  /* THE SOIL BY A RED ALDER ROTATION IS  *,F5.1,*  KG/HA/YR*)
      WRITE(6,124)ALDERF
124   FORMAT(*0ASSUME THE NET ANNUAL INCREMENT OF NITROGEN ADDED TO*,
     1  /* THE FOREST FLOOR BY A RED ALDER ROTATION IS  *,F5.1,
     2  *  KG/HA/YR*)
      GO TO 70
50    WRITE(6,120)
120   FORMAT(* *,//,* NO FERTILIZATION*)
      GO TO 70
60    WRITE(6,123)
123   FORMAT(* *,//,* ADD NITROGEN FERTILIZER*)
C
C**READ IN INITIAL VALUES FOR STATE VARIABLES
C
70    READ(5,101)(SS(I),I=1,8)
101   FORMAT(8(F6.1,2X))
      WRITE(6,131)(SS(I),I=1,8)
131   FORMAT(* *,//,* INITIAL VALUES OF STATE VARIABLES*,/,*0*,
     1  8(F6.1,2X))
C
C**INITIALIZE COUNTER FOR THE NUMBER OF THE CURRENT ROTATION (NRT)
C
      NRT=1
C
C**INITIALIZE TIME AT LAST HARVEST TO ZERO; INITIALIZE LEACHING, HARVESTING,
C  SLASH + EROSION INDICATOR VARIABLES; INITIALIZE INDEX (IJK) OF ARRAYS
C  IN SUBROUTINE STORE; INITIALIZE COUNTER (JINDEX) USED IN F45 AND F50;
C  INITIALIZE TIME AT LAST UREA FERTILIZATION AND FERTILIZATION INDICATOR
C  VARIABLES; INITIALIZE COUNTER KINDEX
C
      TLASTH=TLASTF=0.0
      INDL=INDWTH=INDBH=INDS=INDE=IND45=INDF1=INDF2=INDF3=INDA=0
      INDA2=0
      IJK=0
      JINDEX=KINDEX=0
C
C**INITIALIZE COUNTER USED IN F45 AFTER HARVESTING WITH SLASH LEFT IN PLACE
C  INITIALIZE VARIABLES USED IN F45
C
```

```
      KOUNT=0
      SLASHN=REMAIN=0.0
C
C**SCHEDULE FIRST HARVESTING EVENT AND A TIME EVENT ONE YEAR AFTER
C  HARVESTING TO RESET APPROPRIATE INDICATOR VARIABLES
C
      ATRIB(1)=RL
      ATRIB(2)=1.0
      ATRIB(3)=US
      ATRIB(4)=ST
      CALL FILEM(1)
C
      ATRIB(1)=RL+1.0
      ATRIB(2)=3.0
      ATRIB(3)=0.0
      ATRIB(4)=0.0
      CALL FILEM(1)
C
C**IF APPROPRIATE, SCHEDULE THE FIRST NITROGEN FERTILIZATION EVENT
C
      IF(JF.EQ.0)GO TO 90
      IF(JF.EQ.2)GO TO 80
      ATRIB(1)=36.0
      ATRIB(2)=2.0
      ATRIB(3)=1.0
      ATRIB(4)=0.0
      CALL FILEM(1)
      GO TO 90
C
C**IF APPROPRIATE, SCHEDULE THE FIRST RED ALDER CROP ROTATION
C
80    ATRIB(1)=TNOW+RL
      ATRIB(2)=2.0
      ATRIB(3)=2.0
      ATRIB(4)=0.0
      CALL FILEM(1)
C
90    RETURN
      END
```

```
      SUBROUTINE EVNTS(IX)
C
C**THIS SUBROUTINE TRANSFERS CONTROL TO ONE OF THE EVENT SUBROUTINES
C
      IF(IX.EQ.1)GO TO 10
      IF(IX.EQ.2)GO TO 20
      CALL INDICAT
      GO TO 40
10    CALL HARVST
      GO TO 40
20    CALL FERTIL
C
40    RETURN
      END
```

```
      SUBROUTINE HARVST
      COMMON /GCOM1/ ATRIB(25),JEVNT,MFA,MFE(100),MLE(100),MSTOP,NCRDR,N
     1NAPO,NNAPT,NNATR,NNFIL,NNQ(100),NNTRY,NPRNT,PPARM(50,4),TNOW,TTBEG
     2,TTCLR,TTFIN,TTRIB(25),TTSET
      COMMON /GCOM2/ DD(100),DDL(100),DTFUL,DTNOW,ISEES,LFLAG(50),NFLAG,
     2NNEQD,NNEQS,NNEQT,SS(100),SSL(100),TTNEX
      COMMON/UCOM1/TLASTH,G12(7),G1,G2,G3,G4,G5,PROP(5),G6(41),
     1  G7(41),G8,G9,G10(61),G11(61),PRN,G13(49),G14,REMAIN,SLASHN
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**THIS SUBROUTINE PROCESSES A DOUGLAS-FIR HARVESTING AND SLASH
C  TREATMENT EVENT
C
C  CHECK UTILIZATION STANDARD AND SET APPROPRIATE INDICATOR VARIABLE;
C  SET INDICATOR VARIABLES FOR SOIL LEACHING, SLASH TREATMENT AND
C  SOIL EROSION
C
      IF(ATRIB(3).LE.0.0)INDBH=1
      IF(ATRIB(3).GT.0.0)INDWTH=1
      INDL=1
      IF(ATRIB(3).LE.0.0.AND.ATRIB(4).LE.0.0)INDE=1
      IF(ATRIB(3).LE.0.0.AND.ATRIB(4).GT.0.0)INDE=2
      IF(ATRIB(3).GT.0.0.AND.ATRIB(4).LE.0.0)INDE=3
      IF(ATRIB(3).GT.0.0.AND.ATRIB(4).GT.0.0)INDE=4
      IF(ATRIB(4).LE.0.0)GO TO 5
      INDS=2
      IND45=2
      GO TO 8
C
C**SLASH IS LEFT IN PLACE; SET COUNTER USED IN FUNCTION F45 TO ONE
C
5     KOUNT=1
      INDS=1
      IND45=1
      REMAIN=SS(4)
C
C**REINITIALIZE STAND AGE TO ZERO (BY SETTING TIME AT LAST HARVEST
C  TO TIME NOW)
C
8     TLASTH=TNOW
C
C**SCHEDULE NEXT DOUGLAS-FIR HARVESTING AND SLASH TREATMENT EVENT;
C  NOTE THAT WHEN THE ALDER OPTION IS NOT CHOSEN, ARL WILL EQUAL
C  ZERO AND THE NEXT DOUGLAS-FIR HARVEST WILL BE AT TIME TNOW + RL
C
      IF((TNOW+RL+ARL).GT.TTFIN)GO TO 10
      ATRIB(1)=TNOW+RL+ARL
      ATRIB(2)=1.0
```

```
      ATRIB(3)=ATRIB(3)
      ATRIB(4)=ATRIB(4)
      CALL FILEM(1)
C
C**SCHEDULE A TIME EVENT ONE YEAR FROM THE NEXT HARVEST TO RESET
C  APPROPRIATE INDICATOR VARIABLES
C
      ATRIB(1)=TNOW+RL+ARL+1.0
      ATRIB(2)=3.0
      ATRIB(3)=0.0
      ATRIB(4)=0.0
      CALL FILEM(1)
C
C**INCREMENT THE NUMBER OF THE ROTATION BY ONE
C
      NRT=NRT+1
C
10    RETURN
      END
```

```
      SUBROUTINE INDICAT
      COMMON /GCOM1/ ATRIB(25),JEVNT,MFA,MFE(100),MLE(100),MSTOP,NCRDR,N
     1NAPO,NNAPT,NNATR,NNFIL,NNQ(100),NNTRY,NPRNT,PPARM(50,4),TNOW,TTBEG
     2,TTCLR,TTFIN,TTRIB(25),TTSET
      COMMON /GCOM2/ DD(100),DDL(100),DTFUL,DTNOW,ISEES,LFLAG(50),NFLAG,
     2NNEQD,NNEQS,NNEQT,SS(100),SSL(100),TTNEX
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C  THIS SUBROUTINE RESETS CERTAIN INDICATOR VARIABLES AFTER EITHER
C  A HARVESTING OR UREA FERTILIZATION TIME EVENT
C
      IF(ATRIB(3).GT.0.0)GO TO 10
C
C**IT IS ONE YEAR AFTER A HARVESTING AND SLASH TREATMENT EVENT; RESET
C  APPROPRIATE INDICATOR VARIABLES
C
      INDBH=0
      INDWTH=0
      INDS=0
C
C**REINITIALIZE UNDERSTORY NITROGEN
C
      SS(3)=30.0
      IF(ARL.GT.0.0)SS(3)=0.0
      GO TO 30
10    IF(ATRIB(3).GT.1)GO TO 20
C
C**IT IS ONE YEAR AFTER A UREA FERTILIZATION EVENT; RESET APPROPRIATE
C  INDICATOR VARIABLES
C
      INDF1=0
      GO TO 30
C
C**IT IS THE END OF A RED ALDER ROTATION; RESET APPROPRIATE INDICATOR
C  VARIABLES; REINITIALIZE UNDERSTORY NITROGEN (SS(3))
20    INDA=INDL=INDE=IND45=0
      SS(3)=30.0
C
30    RETURN
      END
```

```
      SUBROUTINE FERTIL
      COMMON /GCOM1/ ATRIB(25),JEVNT,MFA,MFE(100),MLE(100),MSTOP,NCRDR,N
     1NAPO,NNAPT,NNATR,NNFIL,NNQ(100),NNTRY,NPRNT,PPARM(50,4),TNOW,TTBEG
     2,TTCLR,TTFIN,TTRIB(25),TTSET
      COMMON /GCOM2/ DD(100),DDL(100),DTFUL,DTNOW,ISEES,LFLAG(50),NFLAG,
     2NNEQD,NNEQS,NNEQT,SS(100),SSL(100),TTNEX
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**THIS SUBROUTINE PROCESSES FERTILIZATION TIME EVENTS
C
      IF(ATRIB(3).LE.1.0)GO TO 10
      IF(ATRIB(3).GT.1.0)GO TO 20
C
C**NITROGEN FERTILIZATION HAS OCCURRED; SET THE TIME OF THE LAST UREA
C  FERTILIZATION TO TNOW; SET THE UREA FERTILIZATION INDICATOR VARIABLES;
C  SCHEDULE A TIME EVENT TO RESET THE INDICATOR VARIABLE INDF1
C
10    TLASTF=TNOW
      INDF1=INDF2=INDF3=1
      ATRIB(1)=TNOW+1.0
      ATRIB(2)=3.0
      ATRIB(3)=1.0
      ATRIB(4)=0.0
      CALL FILEM(1)
C
C**SCHEDULE THE NEXT UREA FERTILIZATION EVENT
C
      IF(((NRT*RL)+36.0).GT.TTFIN)GO TO 30
      ATRIB(1)=(NRT*RL)+36.0
      ATRIB(2)=2.0
      ATRIB(3)=1.0
      ATRIB(4)=0.0
      CALL FILEM(1)
      GO TO 30
C
C**A RED ALDER CROP ROTATION HAS OCCURRED; SET THE ALDER INDICATOR
C  VARIABLES; SET UNDERSTORY NITROGEN TO ZERO;
C  SCHEDULE A TIME EVENT TO RESET THE INDICATOR VARIABLE INDA AT THE
C  END OF THE ALDER ROTATION
C
20    INDA=INDA2=1
      SS(3)=0.0
      ATRIB(1)=TNOW+ARL
      ATRIB(2)=3.0
      ATRIB(3)=2.0
      ATRIB(4)=0.0
      CALL FILEM(1)
```

```
C
C**SCHEDULE THE NEXT RED ALDER ROTATION
C
      IF((TNOW+ARL+RL).GT.TTFIN)GO TO 30
      ATRIB(1)=TNOW+ARL+RL
      ATRIB(2)=2.0
      ATRIB(3)=2.0
      ATRIB(4)=0.0
      CALL FILEM(1)
C
30    RETURN
      END
```

```
      SUBROUTINE STATE
      COMMON /GCOM1/ ATRIB(25),JEVNT,MFA,MFE(100),MLE(100),MSTOP,NCRDR,N
     1NAPO,NNAPT,NNATR,NNFIL,NNQ(100),NNTRY,NPRNT,PPARM(50,4),TNOW,TTBEG
     2,TTCLR,TTFIN,TTRIB(25),TTSET
      COMMON /GCOM2/ DD(100),DDL(100),DTFUL,DTNOW,ISEES,LFLAG(50),NFLAG,
     2NNEQD,NNEQS,NNEQT,SS(100),SSL(100),TTNEX
      COMMON/UCOM1/TLASTH,G12(7),G1,G2,G3,G4,G5,PROP(5),G6(41),
     1  G7(41),G8,G9,G10(61),G11(61),PRN,G13(49),G14,REMAIN,SLASHN
      COMMON/UCOM2/AGE,IJK
      COMMON/UCOM3/XF04,XF05,XF10,XF14,XF20,XF24,XF30,XF34,XF40,XF45,
     1  XF50,XF51,XF52,XF53,XF60,XF70,XWBVOL,XBRVOL,FOLBIO,WBBIO,BRBIO
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**CALCULATE THE STAND AGE AND THE VALUES OF THE RATE EQUATIONS AT
C  THE PRESENT TIME
C
      IF(ARL.LE.0.0.OR.TLASTH.LE.0.0)GO TO 5
      IF(INDA.EQ.1)AGE=0.0
      IF(INDA.EQ.0)AGE=TNOW-(TLASTH+ARL)
      IF(TNOW.LE.TLASTH+1.0)AGE=0.0
      GO TO 7
 5    AGE=TNOW-TLASTH
C
 7    XF05=F05(AGE)
      XF10=F10(AGE)
      XF14=F14(AGE)
      XF20=F20(AGE)
      XF24=F24(AGE)
      XF30=F30(AGE)
      XF34=F34(AGE)
      XF40=F40(AGE)
      XF45=F45(SS(4))
      XF04=F04(SS(8))
      XF50=F50(AGE)
      XF51=F51(AGE)
      XF52=F52(AGE)
      XF53=F53(AGE)
      XF60=F60(AGE)
      XF70=F70(AGE)
C
C**CALCULATE THE VALUES OF THE STATE VARIABLES USING DIFFERENCE EQUATIONS
C
      SS(1)=SSL(1) + XF51 - XF10 - XF14
      SS(2)=SSL(2) + XF52 - XF20 - XF24
      SS(3)=SSL(3) + XF53 - XF30 - XF34
      SS(4)=SSL(4) + XF04 + XF14 + XF24 + XF34
     1  - XF40 - XF45
```

```
      SS(5)=SSL(5) + XF05 + XF45 - XF50 - XF51
     1  - XF52 - XF53
      XWBVOL=WBVOL(SS(1))
      XBRVOL=BRVOL(SS(2))
      IF(TNOW.LE.TLASTH)GO TO 10
      SS(6)=XWBVOL - XF60
      SS(7)=XBRVOL - XF70
      SS(8)=SS(1)+SS(2)+SS(3)
      GO TO 20
C
C**AFTER A HARVESTING EVENT, INITIALIZE SS(3), SS(6) AND SS(7)
C
10    SS(3)=0.0
      SS(6)=0.0
      SS(7)=0.0
      SS(8)=SS(1) + SS(2) + SS(3)
20    RETURN
      END
```

```
      SUBROUTINE SSAVE
      COMMON /GCOM1/ ATRIB(25),JEVNT,MFA,MFE(100),MLE(100),MSTOP,NCRDR,N
     1NAPO,NNAPT,NNATR,NNFIL,NNQ(100),NNTRY,NPRNT,PPARM(50,4),TNOW,TTBEG
     2,TTCLR,TTFIN,TTRIB(25),TTSET
      COMMON /GCOM2/ DD(100),DDL(100),DTFUL,DTNOW,ISEES,LFLAG(50),NFLAG,
     2NNEQD,NNEQS,NNEQT,SS(100),SSL(100),TTNEX
      COMMON/UCOM1/TLASTH,G12(7),G1,G2,G3,G4,G5,PROP(5),G6(41),
     1  G7(41),G8,G9,G10(61),G11(61),PRN,G13(49),G14,REMAIN,SLASHN
      COMMON/UCOM2/AGE,IJK
      COMMON/UCOM3/XF04,XF05,XF10,XF14,XF20,XF24,XF30,XF34,XF40,XF45,
     1  XF50,XF51,XF52,XF53,XF60,XF70,XWBVOL,XBRVOL,FOLBIO,WBBIO,BRBIO
      COMMON/UCOM4/INOUT,UPTAKE,LITTERF
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
      REAL LITTERF,INOUT
      DIMENSION TABLE1(9),TABLE2(8),PLOT1(3),PLOT2(2),PLOT4(3),
     1  PLOT5(3),PLOT6(3),PLOT3(3),PLOT7(5)
C
C**STORE, FOR LATER PRINTOUT, THE VALUES FOR NITROGEN AND VOLUME REMOVED
C  BY HARVESTING AND SLASH TREATMENT
C
      IF(TNOW.GE.(TLASTH+1.0))GO TO 10
      IF(INDBH.GT.0.OR.INDWTH.GT.0)CALL STORE
C
C**PREPARE TABLE OF STATE VARIABLES
C
10    CALL GPLOT(SS,TNOW,1)
C
C**PREPARE TABLES OF NITROGEN FLOW RATES
C
      TABLE1(1)=XF51
      TABLE1(2)=XF14
      TABLE1(3)=XF10
      TABLE1(4)=XF52
      TABLE1(5)=XF24
      TABLE1(6)=XF20
      TABLE1(7)=XF53
      TABLE1(8)=XF34
      TABLE1(9)=XF30
      CALL GPLOT(TABLE1,TNOW,2)
C
      TABLE2(1)=AGE
      TABLE2(2)=XF04
      TABLE2(3)=XF45
      TABLE2(4)=XF40
      TABLE2(5)=XF05
      TABLE2(6)=XF50
      TABLE2(7)=XF60
      TABLE2(8)=XF70
```

```
      CALL GPLOT(TABLE2,TNOW,3)
C
C**PREPARE PLOTS
C
      PLOT1(1)=SS(1)
      PLOT1(2)=SS(2)
      PLOT1(3)=SS(3)
      CALL GPLOT(PLOT1,TNOW,4)
C
      PLOT2(1)=SS(4)
      PLOT2(2)=SS(5)
      CALL GPLOT(PLOT2,TNOW,5)
C
      PLOT4(1)=XF51
      PLOT4(2)=XF52
      PLOT4(3)=XF53
      CALL GPLOT(PLOT4,TNOW,6)
C
      PLOT5(1)=XF04
      PLOT5(2)=XF45
      PLOT5(3)=XF50
      CALL GPLOT(PLOT5,TNOW,7)
C
      PLOT6(1)=XF14
      PLOT6(2)=XF24
      PLOT6(3)=XF34
      CALL GPLOT(PLOT6,TNOW,8)
C
      INOUT=XF04+XF05-XF10-XF20-XF30-XF40-XF50
      UPTAKE=XF51+XF52+XF53
      LITTERF=XF14+XF24+XF34
      PLOT3(1)=INOUT
      PLOT3(2)=UPTAKE
      PLOT3(3)=LITTERF
      CALL GPLOT(PLOT3,TNOW,9)
C
      PLOT7(1)=WBBIO
      PLOT7(2)=BRBIO
      PLOT7(3)=FOLBIO
      PLOT7(4)=XWBVOL
      PLOT7(5)=XBRVOL
      CALL GPLOT(PLOT7,TNOW,10)
C
      RETURN
      END
```

```
      SUBROUTINE STORE
      COMMON /GCOM1/ ATRIB(25),JEVNT,MFA,MFE(100),MLE(100),MSTOP,NCRDR,N
     1NAPO,NNAPT,NNATR,NNFIL,NNQ(100),NNTRY,NPRNT,PPARM(50,4),TNOW,TTBEG
     2,TTCLR,TTFIN,TTRIB(25),TTSET
      COMMON/UCOM2/AGE,IJK
      COMMON/UCOM3/XF04,XF05,XF10,XF14,XF20,XF24,XF30,XF34,XF40,XF45,
     1  XF50,XF51,XF52,XF53,XF60,XF70,XWBVOL,XBRVOL,FOLBIO,WBBIO,BRBIO
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
      COMMON/UCOM6/SF10(10),SF20(10),SF30(10),SF40(10),SF60(10),
     1  SF70(10),STIME(10),SFOLBIO(10)
C
C**THIS SUBROUTINE STORES TABLES OF:
C  1.  NITROGEN REMOVED IN THE VEGETATION AND FOREST FLOOR AFTER
C      HARVESTING AND SLASH TREATMENT
C  2.  DOUGLAS-FIR VOLUME REMOVED BY HARVESTING
C
      IJK=IJK+1
      STIME(IJK)=TNOW
      SF10(IJK)=XF10
      SF20(IJK)=XF20
      SF30(IJK)=XF30
      SF40(IJK)=XF40
      SF60(IJK)=XF60
      SF70(IJK)=XF70
      SFOLBIO(IJK)=FOLBIO
      IF(INDBH.EQ.1)SFOLBIO(IJK)=0.0
C
      RETURN
      END
```

```
      SUBROUTINE OTPUT
      COMMON/UCOM2/AGE,IJK
      COMMON/UCOM3/XF04,XF05,XF10,XF14,XF20,XF24,XF30,XF34,XF40,XF45,
     1  XF50,XF51,XF52,XF53,XF60,XF70,XWBVOL,XBRVOL,FOLBIO,WBBIO,BRBIO
      COMMON/UCOM6/SF10(10),SF20(10),SF30(10),SF40(10),SF60(10),
     1  SF70(10),STIME(10),SFOLBIO(10)
      DIMENSION CUFTW(10),CUFTBR(10),ITIME(10),ISF10(10),ISF20(10),
     1ISF30(10),ISF40(10),ISF60(10),ICUFTW(10),ISF70(10),ICUFTBR(10),
     2IFOLBIO(10)
C
C**THIS SUBROUTINE OUTPUTS TABLES OF:  1.  NITROGEN REMOVED FROM THE
C  SYSTEM AFTER HARVESTING AND SLASH TREATMENT, AND 2.  DOUGLAS-FIR
C  VOLUME REMOVED BY HARVESTING
C
      WRITE(6,101)
101   FORMAT(*1    NITROGEN REMOVED BY HARVESTING AND SLASH TREATMENT
     1  *,/////,* *,T8,*TIME*,T16,*DOUGLAS-FIR*,T35,*UNDERSTORY*,
     2  T48,*FOREST*,/,* *,T16,*NITROGEN*,T35,*NITROGEN*,T48,*FLOOR N*,
     3  /,* *,T8,*(YRS)*,T16,*(KG/HA)*,T35,*(KG/HA)*,T48,*(KG/HA)*,//,
     4  * *,T16,*WOOD/  FOLIAGE/*,/,* *,T16,*BARK   BRANCHES*,///)
C
      IT1=IT2=IT3=IT4=0.0
      DO 10 J=1,IJK
        ITIME(J)=STIME(J)+.5
        ISF10(J)=SF10(J)+.5
        ISF20(J)=SF20(J)+.5
        ISF30(J)=SF30(J)+.5
        ISF40(J)=SF40(J)+.5
        WRITE(6,102)ITIME(J),ISF10(J),ISF20(J),ISF30(J),ISF40(J)
102     FORMAT(* *,T8,I5,T16,I6,T24,I6,T37,I6,T48,I7,/)
        IT1=IT1 + ISF10(J)
        IT2=IT2 + ISF20(J)
        IT3=IT3 + ISF30(J)
        IT4=IT4 + ISF40(J)
10    CONTINUE
C
      WRITE(6,103)IT1,IT2,IT3,IT4
103   FORMAT(* *,//,* *,T8,*TOTAL*,T16,I6,T24,I6,T37,I6,
     1  T48,I7,////////)
C
C**CALCULATE VOLUME REMOVED IN CU FT/ACRE; WRITE OUT TABLE 2
C
      WRITE(6,104)
104   FORMAT(* *,///,*      DOUGLAS-FIR VOLUME AND BIOMASS REMOVED BY HAR
     1VESTING*,/////,* *,T7,*TIME    WOOD + BARK VOLUME*,T40,*BRANCH VOL
     2UME*,T65,*FOLIAGE*,/,* *,T65,*BIOMASS*,/,* *,T7,*(YRS)*,T15,*(CU M
     3/HA)  (CU FT/AC)    (CU M/HA)  (CU FT/AC)    (KG/HA)*,///)
C
      IU1=IU2=IU3=IU4=IU5=0.0
```

```
      DO 30 K=1,IJK
        CUFTW(K)=14.29*SF60(K)
        CUFTBR(K)=14.29*SF70(K)
        ITIME(K)=STIME(K)+.5
        ISF60(K)=SF60(K)+.5
        ICUFTW(K)=CUFTW(K)+.5
        ISF70(K)=SF70(K)+.5
        ICUFTBR(K)=CUFTBR(K)+.5
        IFOLBIO(K)=SFOLBIO(K)+.5
        WRITE(6,105)ITIME(K),ISF60(K),ICUFTW(K),ISF70(K),ICUFTBR(K),
     1    IFOLBIO(K)
105     FORMAT(* *,T7,I4,3X,I9,2X,I10,4X,I9,3X,I9,4X,I7,/)
        IU1=IU1 + ISF60(K)
        IU2=IU2 + ICUFTW(K)
        IU3=IU3 + ISF70(K)
        IU4=IU4 + ICUFTBR(K)
        IU5=IU5 + IFOLBIO(K)
30    CONTINUE
C
      WRITE(6,106)IU1,IU2,IU3,IU4,IU5
106   FORMAT(* *,//,* *,T7,*TOTAL  *,I9,2X,I10,4X,I9,3X,I9,4X,
     1  I7,//)
C
      RETURN
      END
```

```
      FUNCTION F04(SS8)
      COMMON /GCOM1/ ATRIB(25),JEVNT,MFA,MFE(100),MLE(100),MSTOP,NCRDR,N
     1NAPO,NNAPT,NNATR,NNFIL,NNQ(100),NNTRY,NPRNT,PPARM(50,4),TNOW,TTBEG
     2,TTCLR,TTFIN,TTRIB(25),TTSET
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
      COMMON/UCOM1/TLASTH,G12(7),G1,G2,G3,G4,G5,PROP(5),G6(41),
     1  G7(41),G8,G9,G10(61),G11(61),PRN,G13(49),G14,REMAIN,SLASHN
C
C**F04 = G8 + G9 + G14  WHERE G8 = RATE OF NITROGEN INPUT FROM PRECIPITATION
C  PLUS STEMFLOW AND THROUGHFALL (BASED ON DATA FROM COLE ET AL. 1968
C  AND TURNER 1975); G9 = BASE RATE OF NITROGEN INPUT TO THE FOREST FLOOR
C  FROM NITROGEN FIXATION  (ASSUME G9 = 1.0 KG/HA/YR BASED ON
C  SYLVESTER, 1980 UNPUBLISHED DATA); G14 = RATE OF NITROGEN INPUT TO THE
C  FOREST FLOOR FROM UREA FERTILIZATION
C
C  JINDEX IS SET IN FUNCTION F45 AND IS USED TO PREVENT A RATE FROM BEING
C  CALCULATED TWICE IN ONE YEAR (WHEN A HARVEST EVENT OCCURS); JINDEX IS
C  RESET IN F50
C
C  KINDEX IS A COUNTER SET IN F14
C
      IF(INDA.EQ.1)GO TO 15
      G8=1.1 + (SS8/(91.2553 + .0706167 * SS8))
      IF(SS8.LE.0.0)G8=1.1
      G9=1.0
      G14=0.0
C
C**IF UREA FERTILIZATION HAS OCCURRED, INCREASE F04 BY 220 KG/HA
C
      IF(INDF1.EQ.1.AND.TNOW.LE.TLASTF)G14=220.0
      IF(JINDEX.EQ.1.OR.JINDEX.EQ.3)GO TO 10
      IF(KINDEX.EQ.1.OR.KINDEX.EQ.3)GO TO 10
      F04=G8 + G9 + G14
      GO TO 20
C
**F04 HAS ALREADY BEEN CALCULATED FOR THIS YEAR; SET F04 TO ZERO SO THAT
C  F04 WILL NOT OCCUR TWICE AT THE END OF AN EVENT TIME
C
10    F04=G14
      GO TO 20
C
C**A RED ALDER ROTATION IS IN PROGRESS
C
15    F04=ALDERF
C
20    RETURN
      END
```

```
      FUNCTION F05(AGE)
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**NITROGEN INPUT RATE TO THE SOIL FROM NITROGEN FIXATION; THIS
C  RATE IS ZERO, UNLESS A RED ALDER FERTILIZATION EVENT OCCURS
C
      F05=0.0
      IF(INDA.EQ.1)F05=ALDERN
C
      RETURN
      END
      FUNCTION F10(AGE)
      COMMON /GCOM2/ DD(100),DDL(100),DTFUL,DTNOW,ISEES,LFLAG(50),NFLAG,
     2NNEQD,NNEQS,NNEQT,SS(100),SSL(100),TTNEX
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**LOSS OF NITROGEN FROM DOUGLAS-FIR WOOD AND BARK DUE TO HARVESTING;
C  F10 IS ALWAYS ZERO UNLESS A HARVESTING TIME EVENT OCCURS
C
      IF(INDA.EQ.1)GO TO 5
      IF(INDBH.GT.0)GO TO 10
      IF(INDWTH.GT.0)GO TO 20
 5    F10=0.0
      GO TO 30
C
C**BOLE ONLY HARVESTING HAS OCCURRED
C
10    TAKE1=0.94*SS(1)
      F10=TAKE1
      GO TO 30
C
C**WHOLE TREE HARVESTING HAS OCCURRED
C
20    F10=SS(1)
C
30    RETURN
      END
```

```
      FUNCTION F14(AGE)
      COMMON /GCOM1/ ATRIB(25),JEVNT,MFA,MFE(100),MLE(100),MSTOP,NCRDR,N
     1NAPO,NNAPT,NNATR,NNFIL,NNQ(100),NNTRY,NPRNT,PPARM(50,4),TNOW,TTBEG
     2,TTCLR,TTFIN,TTRIB(25),TTSET
      COMMON/UCOM1/TLASTH,G12(7),G1,G2,G3,G4,G5,PROP(5),G6(41),
     1 G7(41),G8,G9,G10(61),G11(61),PRN,G13(49),G14,REMAIN,SLASHN
      COMMON /GCOM2/ DD(100),DDL(100),DTFUL,DTNOW,ISEES,LFLAG(50),NFLAG,
     2NNEQD,NNEQS,NNEQT,SS(100),SSL(100),TTNEX
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**FLOW OF NITROGEN FROM THE DOUGLAS-FIR WOOD AND BARK TO THE FOREST
C  FLOOR (STEM LITTERFALL); GENERATE A UNIFORM RANDOM DEVIATE; I WILL
C  ASSUME THAT IF AGE IS BETWEEN:
C   0 AND 20, THE PROBABILITY OF STEM LITTERFALL OCCURRING IS .10
C  21 AND 40, THE PROBABILITY OF STEM LITTERFALL OCCURRING IS .15
C  41 AND 60, THE PROBABILITY OF STEM LITTERFALL OCCURRING IS .18
C  61 AND 80, THE PROBABILITY OF STEM LITTERFALL OCCURRING IS .18
C  81 AND 100, THE PROBABILITY OF STEM LITTERFALL OCCURRING IS .20
C 100 AND 120, THE PROBABILITY OF STEM LITTERFALL OCCURRING IS .20
C  IF IT IS FOUND THAT STEM LITTERFALL DOES OCCUR IN THAT YEAR, THE
C  AMOUNT OF LITTERFALL IS A FUNCTION OF STAND AGE (BASED ON TURNER´S DATA))
C
C  PRN = PSEUDO-RANDOM NUMBER GENERATED FROM A UNIFORM (0,1) DISTRIBUTION
C
      IF(INDA.EQ.1)GO TO 80
      IF(INDBH.GT.0)GO TO 70
      IF(INDWTH.GT.0)GO TO 80
C
C**INCREMENT KINDEX BY ONE; KINDEX IS A COUNTER SET IN F14 AND
C  RESET IN F53; KINDEX IS USED TO PREVENT A RATE FROM BEING CALCULATED
C  TWICE IN ONE YEAR (WHEN A FERTILIZATION EVENT OCCURS)
C
      IF(INDF2.EQ.1.AND.TNOW.LE.(TLASTF+1.0))KINDEX=KINDEX+1
      PRN=DRAND(1)
C
      IF(AGE.GT.20)GO TO 10
      IF(PRN.LE.0.10)GO TO 50
      GO TO 60
C
10    IF(AGE.GT.40)GO TO 20
      IF(PRN.LE.0.15)GO TO 50
      GO TO 60
C
20    IF(AGE.GT.60)GO TO 30
      IF(PRN.LE.0.18)GO TO 50
      GO TO 60
C
```

```
30    IF(AGE.GT.80)GO TO 40
      IF(PRN.LE.0.18)GO TO 50
      GO TO 60
C
40    IF(AGE.GT.100)GO TO 45
      IF(PRN.LE.0.20)GO TO 50
      GO TO 60
C
45    IF(PRN.LE.0.20)GO TO 50
      GO TO 60
C
C**STEM LITTERFALL HAS OCCURRED; DETERMINE THE AMOUNT
C
50    F14=GTABL(G12,AGE,0.0,120.0,20.0)
      GO TO 85
C
C**STEM LITTERFALL HAS NOT OCCURRED; SET F14 EQUAL TO ZERO
C
60    F14=0.0
      GO TO 85
C
C**BOLE ONLY HARVESTING HAS OCCURRED
C
70    F14=SS(1)-TAKE1
      SLASHN=SLASHN+(SS(1)-TAKE1)
      GO TO 90
C
C**WHOLE TREE HARVESTING HAS OCCURRED; OR, A RED ALDER ROTATION IS
C  IN PROGRESS
C
80    F14=0.0
      GO TO 90
85    IF(KINDEX.EQ.1.OR.KINDEX.EQ.3)F14=0.0
C
90    RETURN
      END
```

```
      FUNCTION F20(AGE)
      COMMON /GCOM2/ DD(100),DDL(100),DTFUL,DTNOW,ISEES,LFLAG(50),NFLAG,
     2NNEQD,NNEQS,NNEQT,SS(100),SSL(100),TTNEX
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**FLOW OF NITROGEN FROM DOUGLAS-FIR FOLIAGE AND BRANCHES OUT OF THE SYSTEM;
C  F20 WILL ALWAYS BE ZERO EXCEPT WHEN A WHOLE TREE HARVESTING EVENT OCCURS
C
      IF(INDA.EQ.1)GO TO 5
      IF(INDBH.GT.0)GO TO 10
      IF(INDWTH.GT.0)GO TO 20
 5    F20=0.0
      GO TO 30
C
C**BOLE ONLY HARVESTING HAS OCCURRED
C
10    F20=0.0
      GO TO 30
C
C**WHOLE TREE HARVESTING HAS OCCURRED
C
20    TAKE2=0.90*SS(2)
      F20=TAKE2
C
30    RETURN
      END
```

```
      FUNCTION F24(AGE)
      COMMON /GCOM1/ ATRIB(25),JEVNT,MFA,MFE(100),MLE(100),MSTOP,NCRDR,N
     1NAPO,NNAPT,NNATR,NNFIL,NNQ(100),NNTRY,NPRNT,PPARM(50,4),TNOW,TTBEG
     2,TTCLR,TTFIN,TTRIB(25),TTSET
      COMMON /GCOM2/ DD(100),DDL(100),DTFUL,DTNOW,ISEES,LFLAG(50),NFLAG,
     2NNEQD,NNEQS,NNEQT,SS(100),SSL(100),TTNEX
      COMMON/UCOM1/TLASTH,G12(7),G1,G2,G3,G4,G5,PROP(5),G6(41),
     1  G7(41),G8,G9,G10(61),G11(61),PRN,G13(49),G14,REMAIN,SLASHN
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**FLOW OF NITROGEN FROM DOUGLAS-FIR FOLIAGE AND BRANCHES TO THE FOREST
C  FLOOR; LOOK UP VALUES FOR F24 FROM TABLE G10
C
      IF(INDA.EQ.1)GO TO 25
      IF(INDBH.GT.0)GO TO 10
      IF(INDWTH.GT.0)GO TO 20
      F24=GTABL(G10,AGE,0.0,120.0,2.0)
C
C**UREA FERTILIZATION HAS OCCURRED IN THE LAST YEAR; FOLIAGE AND BRANCH
C  LITTERFALL IS DECREASED
C
      IF(INDF1.EQ.1.AND.TNOW.LE.TLASTF)F24=.922*F24
C
C**IF F24 HAS ALREADY BEEN CALCULATED THIS YEAR, SET F24 TO ZERO
C
      IF(KINDEX.EQ.1.OR.KINDEX.EQ.3)F24=0.0
      GO TO 30
C
C**BOLE ONLY HARVESTING HAS OCCURRED
C
10    F24=SS(2)
      SLASHN=SLASHN+SS(2)
      GO TO 30
C
C**WHOLE TREE HARVESTING HAS OCCURRED
C
20    F24=SS(2)-TAKE2
      SLASHN=SLASHN+(SS(2)-TAKE2)
      GO TO 30
C
C**A RED ALDER ROTATION IS IN PROGRESS
C
25    F24=0.0
C
30    RETURN
      END
```

```
      FUNCTION F30(AGE)
      COMMON /GCOM2/ DD(100),DDL(100),DTFUL,DTNOW,ISEES,LFLAG(50),NFLAG,
     2NNEQD,NNEQS,NNEQT,SS(100),SSL(100),TTNEX
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**FLOW OF NITROGEN FROM ABOVEGROUND UNDERSTORY VEGETATION OUT OF THE SYSTEM;
C  THIS RATE WILL BE ZERO UNLESS AN INTENSIVE SLASH TREATMENT EVENT OCCURS
C
      IF(INDA.EQ.1)GO TO 5
      IF(INDS.GT.0)GO TO 10
  5   F30=0.0
      GO TO 30
10    IF(INDS.GT.1)GO TO 20
C
C
C**HARVESTING HAS OCCURRED; NO SLASH TREATMENT
C
      F30=0.0
      GO TO 30
C
C**HARVESTING HAS OCCURRED; REMOVE SLASH
C
20    TAKE3=0.90*SS(3)
      F30=TAKE3
C
30    RETURN
      END
```

```
      FUNCTION F34(AGE)
      COMMON /GCOM2/ DD(100),DDL(100),DTFUL,DTNOW,ISEES,LFLAG(50),NFLAG,
     2NNEQD,NNEQS,NNEQT,SS(100),SSL(100),TTNEX
      COMMON/UCOM1/TLASTH,G12(7),G1,G2,G3,G4,G5,PROP(5),G6(41),
     1  G7(41),G8,G9,G10(61),G11(61),PRN,G13(49),G14,REMAIN,SLASHN
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**FLOW OF NITROGEN FROM THE ABOVEGROUND UNDERSTORY VEGETATION TO THE
C  FOREST FLOOR (UNDERSTORY LITTERFALL); LOOK UP VALUES FOR F34 FROM
C  TABLE G7
C
      IF(INDA.EQ.1)GO TO 55
      IF(INDWTH.GT.0)GO TO 20
      IF(INDBH.GT.0)GO TO 40
      IF(KINDEX.EQ.1.OR.KINDEX.EQ.3)GO TO 55
10    F34=GTABL(G7,AGE,0.0,120.0,3.0)
      GO TO 60
20    IF(INDS.GT.1)GO TO 30
C
C**WHOLE TREE HARVESTING HAS OCCURRED; LEAVE SLASH IN PLACE
C
      F34=SS(3)
      SLASHN=SLASHN+SS(3)
      GO TO 60
C
C**WHOLE TREE HARVESTING HAS OCCURRED; REMOVE SLASH
C
30    F34=SS(3)-TAKE3
      GO TO 60
40    IF(INDS.GT.1)GO TO 50
C
C**BOLE ONLY HARVESTING HAS OCCURRED; LEAVE SLASH IN PLACE
C
      F34=SS(3)
      SLASHN=SLASHN+SS(3)
      GO TO 60
C
C**BOLE ONLY HARVESTING HAS OCCURRED; REMOVE SLASH
C
50    GO TO 30
C
C**F34 HAS ALREADY BEEN CALCULATED THS YEAR; SET F34 TO ZERO; OR A
C  RED ALDER ROTATION IS IN PROGRESS
C
55    F34=0.0
C
60    RETURN
      END
```

```
      FUNCTION F40(AGE)
      COMMON /GCOM1/ ATRIB(25),JEVNT,MFA,MFE(100),MLE(100),MSTOP,NCRDR,N
     1NAPO,NNAPT,NNATR,NNFIL,NNQ(100),NNTRY,NPRNT,PPARM(50,4),TNOW,TTBEG
     2,TTCLR,TTFIN,TTRIB(25),TTSET
      COMMON /GCOM2/ DD(100),DDL(100),DTFUL,DTNOW,ISEES,LFLAG(50),NFLAG,
     2NNEQD,NNEQS,NNEQT,SS(100),SSL(100),TTNEX
      COMMON/UCOM1/TLASTH,G12(7),G1,G2,G3,G4,G5,PROP(5),G6(41),
     1  G7(41),G8,G9,G10(61),G11(61),PRN,G13(49),G14,REMAIN,SLASHN
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**FLOW OF NITROGEN FROM THE FOREST FLOOR OUT OF THE SYSTEM DUE TO
C  VOLATILIZATION (G1; LOSS TO THE ATMOSPHERE) AND LITTER REMOVAL AFTER
C  HARVESTING (G2); ASSUME THE NATURAL VOLATILIZATION RATE IN AN
C  UNFERTILIZED UNBURNED FOREST STAND IS ZERO (KEENEY 1980)
C  ASSUME THE LOSS DUE TO LITTER REMOVAL IS ZERO UNLESS AN INTENSIVE
C  HARVEST TIME EVENT OCCURS
C
      IF(INDA.EQ.1)GO TO 30
      G1=0.0
C
C**IF UREA FERTILIZATION OCCURS, 4.24 PERCENT OF THE ADDED NITROGEN IS
C  LOST TO VOLATILIZATION (.0424 * 220 = 9.3)
C
      IF(INDF1.EQ.1.AND.TNOW.LE.TLASTF)G1=9.3
      IF(INDS.GT.0)GO TO 10
C
C**HARVESTING HAS NOT OCCURRED
C
 5    G2=0.0
      GO TO 20
C
C**HARVESTING HAS OCCURRED; SLASH IS REMOVED
C
10    IF(TNOW.GE.(TLASTH+1.0))GO TO 5
      IF(INDS.GT.1)G2=0.90*SS(4)
C
C**HARVESTING HAS OCCURRED; LEAVE SLASH IN PLACE
C
      IF(INDS.LE.1)G2=0.0
20    F40=G1 + G2
      GO TO 40
C
C**A RED ALDER ROTATION IS IN PROGRESS
C
30    F40=0.0
40    RETURN
      END
```

```
      FUNCTION F45(SS4)
      COMMON /GCOM1/ ATRIB(25),JEVNT,MFA,MFE(100),MLE(100),MSTOP,NCRDR,N
     1NAPO,NNAPT,NNATR,NNFIL,NNQ(100),NNTRY,NPRNT,PPARM(50,4),TNOW,TTBEG
     2,TTCLR,TTFIN,TTRIB(25),TTSET
      COMMON /GCOM2/ DD(100),DDL(100),DTFUL,DTNOW,ISEES,LFLAG(50),NFLAG,
     2NNEQD,NNEQS,NNEQT,SS(100),SSL(100),TTNEX
      COMMON/UCOM1/TLASTH,G12(7),G1,G2,G3,G4,G5,PROP(5),G6(41),
     1  G7(41),G8,G9,G10(61),G11(61),PRN,G13(49),G14,REMAIN,SLASHN
      COMMON/UCOM3/XF04,XF05,XF10,XF14,XF20,XF24,XF30,XF34,XF40,XF45,
     1  XF50,XF51,XF52,XF53,XF60,XF70,XWBVOL,XBRVOL,FOLBIO,WBBIO,BRBIO
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**FLOW OF NITROGEN FROM THE FOREST FLOOR TO THE SOIL
C  USE TABLE OF LOOK UP VALUES (G13(I)) UNLESS HARVESTING OR
C  FERTILIZATION OCCURS
C
      IF(INDA.EQ.1)GO TO 15
      F45=GTABL(G13,SS4,0.0,960.0,20.0)
C
C**IF UREA FERTILIZATION OCCURS, INCREASE F45 BY 208 KG/HA
C
      IF(INDF1.EQ.1.AND.TNOW.LE.TLASTF)F45=208.0
C
C**IF F45 HAS ALREADY BEEN CALCULATED THIS YEAR, SET F45 TO ZERO
C
      IF(KINDEX.EQ.3)F45=0.0
      IF(IND45.GT.0)GO TO 11
      GO TO 20
C
C**HARVESTING HAS OCCURRED
C
11    IF(TNOW.LE.(TLASTH+1.0))JINDEX=JINDEX+1
      IF(JINDEX.EQ.1.OR.JINDEX.EQ.3)GO TO 15
      IF(IND45.EQ.2)GO TO 35
C
C**SLASH LEFT IN PLACE AFTER HARVESTING
C
      IF(KOUNT.LT.1.OR.KOUNT.GT.11)GO TO 34
C
C**WHEN IT IS ONE YEAR AFTER HARVESTING, STORE THE NITROGEN ACCUMULATED IN THE
C  FOREST FLOOR FROM THE PREVIOUS ROTATION IN REMAIN; STORE THE NITROGEN
C  ADDED AS SLASH IN SLASHN (THIS IS ACCOMPLISHED IN HARVST, F14, F24, F34)
C
C
6     WRITE(11,101)TNOW,SLASHN,REMAIN,KOUNT
101   FORMAT(* *,F5.0,T7,F7.1,2X,F7.1,T29,I2)
```

```
C
C**CALCULATE THE ACCELERATED VALUE OF F45
C
      VALUE=SS(4)-SLASHN-REMAIN
      F45=GTABL(G13,VALUE,0.0,960.0,20.0)+.2057*SLASHN+
     1  .0284*REMAIN
C
C**UPDATE SLASHN AND REMAIN AND INCREMENT COUNTER
C
      SLASHN=SLASHN*.7943
      IF(RL.LT.65.0)B4=.9003
      IF(RL.GE.65.0.AND.RL.LT.100.0)B4=.9330
      IF(RL.GE.100.0)B4=.9716
      REMAIN=REMAIN*B4
      KOUNT=KOUNT+1
      GO TO 20
C
C**IF IT IS MORE THAN 10 YEARS SINCE HARVESTING, RESET THE COUNTER
C
34    KOUNT=0
      SLASHN=REMAIN=0.0
C
C**RESET INDICATOR VARIABLE, IND45, TEN YEARS AFTER HARVESTING
C
35    IF(TNOW.GT.(TLASTH+9.0))IND45=0
      GO TO 20
C
C**F45 HAS ALREADY BEEN CALCULATED; SET F45 TO ZERO SO THAT F45 WILL NOT
C  OCCUR TWICE AT ONE TIME EVENT; OR, A RED ALDER ROTATION IS
C  IN PROGRESS AND JINDEX IS RESET
C
15    F45=0.0
      IF(JINDEX.EQ.2)JINDEX=0
C
20    RETURN
      END
```

```
      FUNCTION F50(AGE)
      COMMON /GCOM1/ ATRIB(25),JEVNT,MFA,MFE(100),MLE(100),MSTOP,NCRDR,N
     1NAPO,NNAPT,NNATR,NNFIL,NNQ(100),NNTRY,NPRNT,PPARM(50,4),TNOW,TTBEG
     2,TTCLR,TTFIN,TTRIB(25),TTSET
      COMMON/UCOM1/TLASTH,G12(7),G1,G2,G3,G4,G5,PROP(5),G6(41),
     1  G7(41),G8,G9,G10(61),G11(61),PRN,G13(49),G14,REMAIN,SLASHN
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**SUM OF NITROGEN LOSSES FROM THE SOIL OUT OF THE SYSTEM;
C  F50 = G3 + G4 + G5 , WHERE:
C  G3 = RATE OF SOIL NITROGEN LOST BY EROSION
C  G4 = RATE OF SOIL NITROGEN LOST BY DENITRIFICATION
C  G5 = RATE OF LEACHING OF SOIL NITROGEN BEYOND THE ROOTING ZONE
C
C  ASSUME G3 AND G4 HAVE THE FOLLOWING CONSTANT RATES (UNLESS HARVESTING
C  OCCURS)
C
      IF(INDA.EQ.1)GO TO 80
      IF(JINDEX.EQ.1.OR.JINDEX.EQ.3)GO TO 80
      G3=0.16
      G4=1.0
      BASEG5=4.0
C
C**IF UREA FERTILIZATION HAS OCCURRED IN THE LAST 5 YEARS, INCREASE G5
C
      IF(INDF2.EQ.0)GO TO 5
      IF(KINDEX.EQ.3)GO TO 80
      G5=1.277*BASEG5
      IF(KINDEX.EQ.1)G5=.277*BASEG5
      GO TO 25
C
C**DETERMINE IF A HARVESTING EVENT HAS OCCURRED IN THE LAST FIVE YEARS
C  (WHEN INDL=1 AND TNOW-TLASTH .LE. 5.0)
C
C  IF A HARVESTING EVENT HAS OCCURRED IN THE LAST FIVE YEARS, INCREASE THE
C  BASE NITROGEN LEACHING RATE IN THE YEAR AFTER HARVESTING TO DOUBLE ITS
C  ORIGINAL VALUE; THE LEACHING RATE WILL THEN DECLINE PROPORTIONATELY TO
C  THE BASE RATE (BASEG5) IN THE SIXTH YEAR AFTER HARVESTING; THE ARRAY
C  PROP(I) GIVES THE PROPORTIONAL INCREASE FROM THE BASE LEACHING RATE
C
C  IF A HARVESTING EVENT HAS NOT OCCURRED IN THE LAST FIVE YEARS, RESET
C  THE INDICATOR VARIABLE, IF NECESSARY; G5 WILL EQUAL THE BASE RATE
C
 5    IF(INDL.LE.0)GO TO 20
      IF((TNOW-TLASTH).LE.0.0)GO TO 20
      IF((TNOW-TLASTH).GT.5.0)GO TO 23
      I=IFIX(TNOW-TLASTH)
      G5=PROP(I) * 2.0 * BASEG5
```

```
      GO TO 25
23    INDL=0
20    G5=BASEG5
C
25    IF(INDE.EQ.0)GO TO 70
C
C**A HARVESTING EVENT HAS OCCURRED IN THE LAST 10 YEARS; INCREASE EROSION
C  LOSS ACCORDINGLY
C
      IF(INDE.EQ.1)GO TO 50
      IF(INDE.EQ.2)GO TO 40
      IF(INDE.EQ.3)GO TO 30
C
C**WHOLE TREE HARVESTING HAS OCCURRED; SLASH REMOVED
C
      IF(TNOW.LE.TLASTH+7.)GO TO 7
      IF(TNOW.LE.TLASTH+8.)GO TO 8
      IF(TNOW.LE.TLASTH+9.)GO TO 9
      IF(TNOW.LE.TLASTH+10.)GO TO 10
      GO TO 60
7     G3=5.8
      GO TO 60
8     G3=4.5
      GO TO 60
9     G3=3.0
      GO TO 60
10    G3=1.5
      GO TO 60
C
C**WHOLE TREE HARVESTING; SLASH LEFT IN PLACE
C
30    IF(TNOW.LE.TLASTH+7.)GO TO 11
      IF(TNOW.LE.TLASTH+8.)GO TO 12
      IF(TNOW.LE.TLASTH+9.)GO TO 13
      IF(TNOW.LE.TLASTH+10.)GO TO 14
      GO TO 60
11    G3=3.0
      GO TO 60
12    G3=2.5
      GO TO 60
13    G3=2.0
      GO TO 60
14    G3=1.5
      GO TO 60
C
C**BOLE ONLY HARVESTING; SLASH REMOVED
C
40    IF(TNOW.LE.TLASTH+8.)GO TO 15
      IF(TNOW.LE.TLASTH+9.)GO TO 16
      IF(TNOW.LE.TLASTH+10.)GO TO 17
```

```
      GO TO 60
15    G3=2.9
      GO TO 60
16    G3=2.0
      GO TO 60
17    G3=1.5
      GO TO 60
C
C**BOLE ONLY HARVESTING; SLASH LEFT IN PLACE
C
50    IF(TNOW.LE.TLASTH+9.)GO TO 18
      IF(TNOW.LE.TLASTH+10.)GO TO 19
      GO TO 60
18    G3=1.5
      GO TO 60
19    G3=1.0
      GO TO 60
C
C**RESET SOIL EROSION INDICATOR VARIABLE IF MORE THAN 10 YEARS HAVE
C  PASSED SINCE THE LAST HARVESTING EVENT
C
60    IF(INDE.EQ.0)GO TO 70
      IF((TNOW-TLASTH).GE.10.0)INDE=0
C
70    F50=G3 + G4 + G5
      IF(KINDEX.EQ.1)F50=G5
      GO TO 90
C
C**F50 HAS ALREADY BEEN CALCULATED; SET F50 TO ZERO SO THAT F50 WILL NOT
C  OCCUR TWICE AT THE END OF THE ROTATION; RESET THE COUNTER (JINDEX);
C  OR, A RED ALDER ROTATION HAS OCCURRED
C
80    F50=0.0
      IF(JINDEX.EQ.3)JINDEX=0
C
90    RETURN
      END
```

```
      FUNCTION F51(AGE)
      COMMON /GCOM1/ ATRIB(25),JEVNT,MFA,MFE(100),MLE(100),MSTOP,NCRDR,N
     1NAPO,NNAPT,NNATR,NNFIL,NNQ(100),NNTRY,NPRNT,PPARM(50,4),TNOW,TTBEG
     2,TTCLR,TTFIN,TTRIB(25),TTSET
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**FLOW OF NITROGEN FROM THE SOIL TO THE DOUGLAS-FIR WOOD AND BARK (WOOD
C  UPTAKE OF NITROGEN FROM THE SOIL); USE REGRESSION EQUATION 6E FOR AGES
C  1 - 85; USE A CONSTANT RATE FOR AGES 86 - 120
C
      IF(INDA.EQ.1)GO TO 20
      IF(INDBH.EQ.1.OR.INDWTH.EQ.1)GO TO 20
      F51 = .4051 * (AGE ** 1.2207) * (.9529 ** AGE)
      IF(AGE.GT.85.0)F51=1.5
      IF(INDA2.EQ.1)GO TO 25
C
C**IF UREA FERTILIZATION HAS OCCURRED IN THE LAST 10 YEARS, INCREASE
C  UPTAKE;  IF 10 YEARS HAVE PASSED SINCE THE FERTILIZATION EVENT, RESET
C  THE INDICATOR VARIABLE INDF3
C
      IF(KINDEX.EQ.1.OR.KINDEX.EQ.3)GO TO 20
      IF(INDF3.EQ.0)GO TO 30
      IF(TNOW.LE.TLASTF+7.)GO TO 7
      IF(TNOW.LE.TLASTF+8.)GO TO 8
      IF(TNOW.LE.TLASTF+9.)GO TO 9
      IF(TNOW.LE.TLASTF+10.)GO TO 10
      IF(TNOW.LE.TLASTF+11.)GO TO 11
      IF(TNOW.LE.TLASTF+12.)GO TO 12
      GO TO 95
7     F51=1.68*F51
      GO TO 95
8     F51=1.6*F51
      GO TO 95
9     F51=1.5*F51
      GO TO 95
10    F51=1.4*F51
      GO TO 95
11    F51=1.3*F51
      GO TO 95
12    F51=1.2*F51
95    IF(TNOW.GT.(TLASTF+11.0))INDF3=0
      GO TO 30
C
C**F51 HAS ALREADY BEEN CALCULATED THIS YEAR; SET F51 TO ZERO; OR, A
C  RED ALDER ROTATION IS IN PROGRESS
C
20    F51=0.0
      GO TO 30
```

```
C
C**UPTAKE IS INCREASED DUE TO A PREVIOUS 15 YEAR ALDER ROTATION
C
25    IF(ARL.GT.15.0)GO TO 27
      F51=B1(1)*F51
      GO TO 30
C
C**UPTAKE IS INCREASED DUE TO A PREVIOUS 40 YEAR ALDER ROTATION
C
27    F51=B1(2)*F51
C
30    RETURN
      END
```

```
      FUNCTION F52(AGE)
      COMMON /GCOM1/ ATRIB(25),JEVNT,MFA,MFE(100),MLE(100),MSTOP,NCRDR,N
     1NAPO,NNAPT,NNATR,NNFIL,NNQ(100),NNTRY,NPRNT,PPARM(50,4),TNOW,TTBEG
     2,TTCLR,TTFIN,TTRIB(25),TTSET
      COMMON/UCOM1/TLASTH,G12(7),G1,G2,G3,G4,G5,PROP(5),G6(41),
     1  G7(41),G8,G9,G10(61),G11(61),PRN,G13(49),G14,REMAIN,SLASHN
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**FLOW OF NITROGEN FROM THE SOIL TO THE DOUGLAS-FIR FOLIAGE AND BRANCHES
C  (FOLIAGE AND BRANCH UPTAKE OF NITROGEN FROM THE SOIL); LOOK UP VALUES
C  OF F52 FROM A TABLE STORED IN ARRAY G11
C
      IF(INDA.EQ.1)GO TO 10
      IF(INDBH.EQ.1.OR.INDWTH.EQ.1)GO TO 10
      F52=GTABL(G11,AGE,0.0,120.0,2.0)
      IF(INDA2.EQ.1)GO TO 15
C
C**IF UREA FERTILIZATION HAS OCCURRED IN THE LAST 7 YEARS, INCREASE UPTAKE
C
      IF(KINDEX.EQ.1.OR.KINDEX.EQ.3)GO TO 10
      IF(INDF2.EQ.0)GO TO 20
      IF(TNOW.LE.TLASTF+1.)GO TO 1
      IF(TNOW.LE.TLASTF+2.)GO TO 2
      IF(TNOW.LE.TLASTF+3.)GO TO 3
      IF(TNOW.LE.TLASTF+4.)GO TO 4
      IF(TNOW.LE.TLASTF+5.)GO TO 5
      IF(TNOW.LE.TLASTF+6.)GO TO 6
      IF(TNOW.LE.TLASTF+7.)GO TO 7
      GO TO 20
1     F52=1.68*F52
      GO TO 20
2     F52=1.58*F52
      GO TO 20
3     F52=1.49*F52
      GO TO 20
4     F52=1.39*F52
      GO TO 20
5     F52=1.29*F52
      GO TO 20
6     F52=1.20*F52
      GO TO 20
7     F52=1.1*F52
      IF(TNOW.LE.TLASTF+1.)F52=1.68*F52
      GO TO 20
C
10    F52=0.0
      GO TO 20
```

```
C
C**UPTAKE IS INCREASED DUE TO A PREVIOUS 15 YEAR ALDER ROTATION
C
15    IF(ARL.GT.15.0)GO TO 18
      F52=B2(1)*F52
      GO TO 20
C
C**UPTAKE IS INCREASED DUE TO A PREVIOUS 40 YEAR ALDER ROTATION
C
18    F52=B2(2)*F52
C
20    RETURN
      END
```

```
      FUNCTION F53(AGE)
      COMMON /GCOM1/ ATRIB(25),JEVNT,MFA,MFE(100),MLE(100),MSTOP,NCRDR,N
     1NAPO,NNAPT,NNATR,NNFIL,NNQ(100),NNTRY,NPRNT,PPARM(50,4),TNOW,TTBEG
     2,TTCLR,TTFIN,TTRIB(25),TTSET
      COMMON/UCOM1/TLASTH,G12(7),G1,G2,G3,G4,G5,PROP(5),G6(41),
     1  G7(41),G8,G9,G10(61),G11(61),PRN,G13(49),G14,REMAIN,SLASHN
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**FLOW OF NITROGEN FROM THE SOIL TO THE NITROGEN IN THE UNDERSTORY
C  VEGETATION (UNDERSTORY UPTAKE OF NITROGEN FROM THE SOIL)
C  LOOK UP VALUES OF F53 FROM A TABLE STORED IN ARRAY G6
C
      IF(INDA.EQ.1)GO TO 10
      IF(INDBH.EQ.1.OR.INDWTH.EQ.1)GO TO 10
      F53=GTABL(G6,AGE,0.0,120.0,3.0)
      IF(INDA2.EQ.1)GO TO 17
C
C**IF UREA FERTILIZATION HAS OCCURRED IN THE LAST 7 YEARS,INCREASE UPTAKE;
C
C  IF  7 YEARS HAVE PASSED SINCE THE FERTILIZATION EVENT, RESET THE
C  INDICATOR VARIABLE INDF2
C
      IF(KINDEX.EQ.1.OR.KINDEX.EQ.3)GO TO 15
      IF(INDF2.EQ.0)GO TO 20
      IF(TNOW.LE.TLASTF+1.)GO TO 1
      IF(TNOW.LE.TLASTF+2.)GO TO 2
      IF(TNOW.LE.TLASTF+3.)GO TO 3
      IF(TNOW.LE.TLASTF+4.)GO TO 4
      IF(TNOW.LE.TLASTF+5.)GO TO 5
      IF(TNOW.LE.TLASTF+6.)GO TO 6
      IF(TNOW.LE.TLASTF+7.)GO TO 7
      GO TO 25
1     F53=1.25*F53
      GO TO 25
2     F53=1.21*F53
      GO TO 25
3     F53=1.17*F53
      GO TO 25
4     F53=1.14*F53
      GO TO 25
5     F53=1.10*F53
      GO TO 25
6     F53=1.07*F53
      GO TO 25
7     F53=1.03*F53
25    IF(TNOW.GT.(TLASTF+6.0))INDF2=0
      GO TO 20
```

```
C
C**HARVESTING HAS OCCURRED; OR, A RED ALDER ROTATION IS IN PROGRESS
C
10    F53=0.0
      GO TO 20
C
C**F53 HAS ALREADY BEEN CALCULATED THIS YEAR; SET F53 TO ZERO ; RESET THE
C  COUNTER KINDEX
C
15    F53=0.0
      IF(KINDEX.EQ.3)KINDEX=0
      GO TO 20
C
C**UPTAKE IS INCREASED DUE TO A PREVIOUS 15 YEAR ALDER ROTATION
C
17    IF(ARL.GT.15.0)GO TO 18
      F53=B3(1)*F53
      GO TO 20
C
C**UPTAKE IS INCREASED DUE TO A PREVIOUS 40 YEAR ALDER ROTATION
C
18    F53=B3(2)*F53
C
20    RETURN
      END
```

```
      FUNCTION WBVOL(SS1)
      COMMON/UCOM3/XF04,XF05,XF10,XF14,XF20,XF24,XF30,XF34,XF40,XF45,
     1  XF50,XF51,XF52,XF53,XF60,XF70,XWBVOL,XBRVOL,FOLBIO,WBBIO,BRBIO
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**THIS FUNCTION CALCULATES DOUGLAS-FIR WOOD AND BARK VOLUME AS A
C  FUNCTION OF DOUGLAS-FIR WOOD AND BARK NITROGEN
C
C  CONVERT WOOD AND BARK NITROGEN (SS1; KG/HA) TO BIOMASS (WBBIO; KG/HA)
C  USING REGRESSION 2 (BASED ON TURNER'S DATA); CONVERT BIOMASS TO
C  VOLUME (WBVOL; CU M/HA) BY ASSUMING A WOOD AND BARK SPECIFIC GRAVITY
C  OF .45
C
      IF(INDA.EQ.1)GO TO 10
      WBBIO=1095.31*SS1
      WBVOL=.001*WBBIO/.45
      GO TO 20
C
C**A RED ALDER ROTATION IS IN PROGRESS
C
10    WBBIO=0.0
      WBVOL=0.0
C
20    RETURN
      END
```

```
      FUNCTION BRVOL(SS2)
      COMMON/UCOM3/XF04,XF05,XF10,XF14,XF20,XF24,XF30,XF34,XF40,XF45,
     1  XF50,XF51,XF52,XF53,XF60,XF70,XWBVOL,XBRVOL,FOLBIO,WBBIO,BRBIO
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**THIS FUNCTION CALCULATES DOUGLAS-FIR FOLIAGE BIOMASS AND BRANCH
C  VOLUME AS A FUNCTION OF DOUGLAS-FIR FOLIAGE AND BRANCH NITROGEN
C
C  CONVERT FOLIAGE AND BRANCH NITROGEN (SS2; KG/HA) TO BIOMASS
C  (FBRBIO; KG/HA) USING REGRESSION 2 (BASED ON TURNER'S DATA);
C  PROPORTION THE FOLIAGE AND BRANCH BIOMASS INTO ITS COMPONENTS
C  (BRBIO AND FOLBIO); CONVERT BRANCH BIOMASS TO BRANCH VOLUME
C  (BRVOL; CU M/HA)
C
      IF(INDA.EQ.1)GO TO 15
      IF(INDWTH.EQ.1.AND.SS2.LE.0.0)GO TO 10
      FBRBIO=167.488*SS2
      BRBIO=1.685749*(FBRBIO**.875182)*(1.000010**FBRBIO)
      FOLBIO=FBRBIO-BRBIO
      BRVOL=.001*BRBIO/.5
      GO TO 20
C
C**IF WHOLE TREE HARVESTING HAS OCCURRED, CALCULATE THE FOLIAGE
C BIOMASS REMOVED; SET BRANCH BIOMASS AND BRANCH VOLUME TO ZERO
C
10    FOLBIO=0.90*FOLBIO
      BRBIO=0.0
      BRVOL=0.0
      GO TO 20
C
C**A RED ALDER ROTATION IS IN PROGRESS
C
15    FOLBIO=0.0
      BRBIO=0.0
C     BRVOL=0.0
20    RETURN
      END
```

```
      FUNCTION F60(AGE)
      COMMON /GCOM1/ ATRIB(25),JEVNT,MFA,MFE(100),MLE(100),MSTOP,NCRDR,N
     1NAPO,NNAPT,NNATR,NNFIL,NNQ(100),NNTRY,NPRNT,PPARM(50,4),TNOW,TTBEG
     2,TTCLR,TTFIN,TTRIB(25),TTSET
      COMMON /GCOM2/ DD(100),DDL(100),DTFUL,DTNOW,ISEES,LFLAG(50),NFLAG,
     2NNEQD,NNEQS,NNEQT,SS(100),SSL(100),TTNEX
      COMMON/UCOM1/TLASTH,G12(7),G1,G2,G3,G4,G5,PROP(5),G6(41),
     1  G7(41),G8,G9,G10(61),G11(61),PRN,G13(49),G14,REMAIN,SLASHN
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**FLOW OF DOUGLAS-FIR WOOD AND BARK VOLUME OUT OF THE SYSTEM; THIS
C  FUNCTION EQUALS ZERO UNLESS A HARVESTING EVENT OCCURS
C
      IF(INDA.EQ.1)GO TO 5
      IF(INDBH.EQ.1.AND.TNOW.LE.TLASTH)GO TO 10
      IF(INDWTH.EQ.1.AND.TNOW.LE.TLASTH)GO TO 20
 5    F60=0.0
      GO TO 30
C
C**BOLE ONLY HARVESTING HAS OCCURRED (ASSUME A 6 PERCENT UNMERCHANTABLE TOP)
C
10    TAKE6=0.94*SS(6)
      F60=TAKE6
      GO TO 30
C
C**WHOLE TREE HARVESTING HAS OCCURRED
C
20    F60=SS(6)
C
30    RETURN
      END
```

```
      FUNCTION F70(AGE)
      COMMON /GCOM2/ DD(100),DDL(100),DTFUL,DTNOW,ISEES,LFLAG(50),NFLAG,
     2NNEQD,NNEQS,NNEQT,SS(100),SSL(100),TTNEX
      COMMON/UCOM5/RL,INDL,INDBH,INDWTH,INDS,INDE,TAKE1,TAKE2,
     1  TAKE3,TAKE6,IND45,JINDEX,INDF1,INDF2,INDF3,INDA,ARL,TLASTF,NRT,
     2  KINDEX,ALDERN,INDA2,ALDERF,B1(2),B2(2),B3(2),KOUNT
C
C**FLOW OF DOUGLAS-FIR BRANCH VOLUME OUT OF THE SYSTEM; THIS
C  FUNCTION EQUALS ZERO UNLESS A HARVESTING EVENT OCCURS
C
      IF(INDA.EQ.1)GO TO 5
      IF(INDWTH.EQ.1)GO TO 10
 5    F70=0.0
      GO TO 20
C
C**WHOLE TREE HARVESTING HAS OCCURRED
C
10    F70=0.90*SS(7)
C
20    RETURN
      END
```

GASP STATE VARIABLES

Variable	Definition	Units	Initial value
SS(1)	Douglas-fir wood and bark nitrogen	kg/ha	Input
SS(2)	Douglas-fir foliage and branch nitrogen	kg/ha	Input
SS(3)	Understory aboveground nitrogen	kg/ha	Input
SS(4)	Total forest floor nitrogen	kg/ha	Input
SS(5)	Total soil nitrogen (within the rooting zone)	kg/ha	Input
SS(6)	Douglas-fir wood and bark volume	m^3/ha	Calculated
SS(7)	Douglas-fir branch volume	m^3/ha	Calculated
SS(8)	Nitrogen in total aboveground vegetation	kg/ha	Calculated

NON-GASP VARIABLES

Variable	Definition	Units	Initial Value
AGE	Age of the forest stand	years	0.0
ALDERF	Net annual increment of nitrogen added to the forest floor by a red alder rotation if ARL = 15, ALDERF = 17.2 if ARL = 40, ALDERF = 15.3	kg/ha/yr	Input
ALDERN	Net annual increment of nitrogen added to the soil by a red alder rotation if ARL = 15, ALDERN = 24.0 if ARL = 40, ALDERN = 26.5	kg/ha/yr	Input
ARL	Red alder rotation length (must be either 15 or 40)	years	Input
B1(I)	Proportional increase in Douglas-fir wood and bark nitrogen uptake following a red alder rotation I = 1 15 year alder rotation I = 2 40 year alder rotation	Unitless	Input
B2(I)	Proportional increase in Douglas-fir foliage and branch nitrogen uptake following a red alder rotation I = 1 15 year alder rotation I = 2 40 year alder rotation	Unitless	Input
B3(I)	Proportional increase in understory nitrogen uptake following a red alder rotation I = 1 15 year alder rotation I = 2 40 year alder rotation	Unitless	Input
BASEG5	Base rate of nitrogen leaching beyond the soil rooting zone (unmanaged forest situation)	kg/ha/yr	4.0

Variable	Definition	Units	Initial Value
BRBIO	Douglas-fir branch biomass	kg/ha	0.0
FBRBIO	Douglas-fir foliage and branch biomass	kg/ha	0.0
FOLBIO	Douglas-fir foliage biomass	kg/ha	0.0
F1	Rate of nitrogen lost from the forest floor to the atmosphere due to amonia volatilization	kg/ha/yr	0.0
G2	Rate of nitrogen lost from the forest floor due to litter removal	kg/ha/yr	0.0
G3	Rate of nitrogen lost from the soil due to erosion	kg/ha/yr	0.0
G4	Rate of nitrogen lost from the soil due to denitrification	kg/ha/yr	1.0
G5	Rate of nitrogen lost from the soil due to leaching beyond the rooting zone	kg/ha/yr	-
G6(I)	Rate of nitrogen uptake from the soil to the understory aboveground vegetation; array stores uptake values in three-year increments; I=1-41	kg/ha/yr	Input
G7(I)	Rate of understory nitrogen litterfall to the forest floor; array stores litterfall values in three-year increments; I=1-41	kg/ha/yr	Input
G8	Rate of nitrogen input to the forest floor from precipitation, dustfall, stemflow and throughfall	kg/ha/yr	Calculated
G9	Rate of nitrogen input to the forest floor from nitrogen fixation within the forest floor	kg/ha/yr	1.0
G10(I)	Rate of Douglas-fir foliage and branch nitrogen litterfall to the forest floor; array stores litterfall values in two-year increments; I=1-61	kg/ha/yr	Input

Variable	Definition	Units	Initial Value
G11(I)	Rate of Douglas-fir foliage and branch nitrogen uptake from the soil; array stores uptake values in two-year increments; I=1-61	kg/ha/yr	Input
G12(I)	Rate of Douglas-fir wood and bark nitrogen litterfall to the forest floor; array stores litterfall values in 20-year increments; I=1-7	kg/ha/yr	Input
G13(I)	Rate of nitrogen transferred from the forest floor to the soil; array stores transfer values in 3-year increments; I=1-41	kg/ha/yr	Input
G14	Rate of nitrogen input to the forest floor from urea fertilization	kg/ha/hr	0.0
JF	Fertilization code JF=0 No fertilization JF=1 Add urea fertilizer JF=2 Alternate Douglas-fir rotation with red alder rotations	Unitless	Input
NRT	Number of the current rotation	Unitless	1
SLASHN	Nitrogen added to the forest floor as slash	kg/ha	Calculated
ST	Slash treatment code ST=0 Leave slash in place ST=1 Remove (or burn) slash	Unitless	Input
US	Utilization standard code US=0 Bole only harvesting US=1 Whole tree harvesting (excluding roots)	Unitless	Input
TLASTF	Time at the last urea fertilization	years	0.0
TLASTH	Time at the last harvest	years	0.0

Variable	Definition	Units	Initial Value
G1	Rate of nitrogen lost from the forest floor to the atmosphere due to ammonia volatilization	kg/ha/yr	0.0
REMAIN	Nitrogen remaining in the forest floor from the previous rotation	kg/ha	Calculated
RL	Douglas-fir rotation length	years	Input

NON-GASP FUNCTIONS

Function	Definition	Units
F04(SS8)	Rate of nitrogen input to the forest floor from precipitation, nitrogen fixation and fertilization	kg/ha/yr
F05(AGE)	Rate of nitrogen input to the soil from nitrogen fixation	kg/ha/yr
F10(AGE)	Rate of loss of nitrogen from Douglas-fir wood and bark out of the system due to harvesting	kg/ha/yr
F14(AGE)	Rate of flow of nitrogen from the Douglas-fir wood and bark to the forest floor (wood and bark litterfall)	kg/ha/yr
F20(AGE)	Rate of loss of nitrogen from Douglas-fir foliage and branches out of the system due to harvesting	kg/ha/yr
F24(AGE)	Rate of flow of nitrogen from Douglas-fir foliage and branches to the forest floor (foliage and branch litterfall)	kg/ha/yr
F30(AGE)	Rate of loss of nitrogen from the above-ground understory vegetation out of the system due to harvesting and slash treatment	kg/ha/yr
F34(AGE)	Rate of flow of nitrogen from the above-ground understory vegetation to the forest floor (understory litterfall)	kg/ha/yr
F40(AGE)	Rate of loss of nitrogen from the forest floor out of the system due to volatilization and litter removal	kg/ha/yr
F45(AGE)	Rate of flow of nitrogen from the forest floor to the soil	kg/ha/yr
F50(AGE)	Rate of nitrogen losses from the soil out of the system (sum of erosion, denitrification and leaching beyond the rooting zone)	kg/ha/yr
F51(AGE)	Rate of flow of nitrogen from the soil to the Douglas-fir wood and bark	kg/ha/yr
F52(AGE)	Rate of flow of nitrogen from the soil to the Douglas-fir foliage and branches	kg/ha/yr

Function	Definition	Units
F53(AGE)	Rate of flow of nitrogen from the soil to the aboveground understory vegetation	kg/ha/yr
F60(AGE)	Rate of flow of Douglas-fir wood and bark volume out of the system due to harvesting	m^3/ha/yr
F70(AGE)	Rate of flow of Douglas-fir branch volume out of the system due to harvesting	m^3/ha/yr
BRVOL(SS1)	Douglas-fir foliage biomass (kg/ha) and branch volume calculated as a function of foliage and branch nitrogen	m^3/ha
WBVOL(SS2)	Douglas-fir wood and bark volume calculated as a function of wood and bark nitrogen	m^3/ha

TIME EVENTS

Definition of Events and Attributes

1. Clearcut harvest and slash treatment

ATRIB (1) - event time

ATRIB (2) - 1 = clearcut harvest and slash treatment event code

ATRIB (3) - 0 = harvest boles only
1 = harvest whole tree, exluding roots

ATRIB (4) - 0 = leave slash in place
1 = remove (or burn) slash

2. Nitrogen fertilization

ATRIB (1) - time of fertilization event

ATRIB (2) - 2 = fertilization event code

ATRIB (3) - 1 = add urea fertilizer
2 = alternate Douglas-fir with red alder rotations

ATRIB (4) - not used

3. Reset indicator variables

ATRIB (1) - event time

ATRIB (2) - 3 = event code

ATRIB (3) - 0 = one year since harvest and slash treatment
1 = one year since urea fertilization
2 = end of red alder rotation

ATRIB (4) - not used

Event Codes and Ranking

Name of subroutine	Event code
HARVST	1
FERTIL	2
INDICAT	3

Secondary ranking for event file: High Value First Based on Attribute 2 (the event code)

The occurrence of a time event triggers the setting of indicator variables; the indicator variables are used in individual function subprograms to calculate transfer rates. The following indicator variables are used:

VARIABLE NAME — DEFINITION

1. INDL - soil leaching indicator variable
    - 0 = base leaching rate
    - 1 = accelerated leaching rate due to harvesting
    - this indicator variable is in operation for 5 years after harvesting; at that time it is reset to zero in FUNCTION F50

2. INDBH - bole harvesting indicator variable
    - 0 = bole harvesting has not occurred in the last year
    - 1 = bole harvesting has occurred in the last year
    - reset in SUBROUTINE INDICAT

3. INDWTH - whole tree harvesting indicator variable
    - 0 = whole tree harvesting has not occurred in the last year
    - 1 = whole tree harvesting has occurred in the last year
    - reset in SUBROUTINE INDICAT

4. INDS - slash indicator variable

1 = leave slash in place

2 = remove slash (or burn)

\- reset in SUBROUTINE INDICAT

5. INDE - soil erosion indicator variable

0 = soil erosion is at base level

1 = soil erosion is accelerated due to bole only harvesting and slash left in place in the last 10 years

2 = soil erosion is accelerated due to bole only harvesting and slash removed in the last 10 years

3 = soil erosion is accelerated due to whole tree harvesting and slash left in place in last 10 years

4 = soil erosion is accelerated due to whole tree harvesting and slash removed in last 10 years

\- reset in FUNCTION F50

6. IND45 - indicator variable for transfer of N from the forest floor to the soil

0 = F45 is at normal preharvesting rate

1 = F45 is accelerated for 10 years due to harvesting with slash left in place

2 = F45 is at normal rate after harvesting with slash removed

\- reset in FUNCTION F45

7. INDF1 - urea fertilization indicator variable 1

   0 = urea fertilization has not occurred in the last year

   1 = urea fertilization has occurred in the last year

   - this indicator variable is reset one year after fertilization (reset in subroutine INDICAT)

8. INDF2 - urea fertilization indicator variable 2

   0 = urea fertilization has not occurred in the last 7 years

   1 = urea fertilization has occurred in the last seven years

   - reset in F53

9. INDF3 - urea fertilization indicator variable 3

   0 = urea fertilization has not occurred in the last 12 years

   1 = urea fertilization has occurred in the last 12 years

   - reset in F51

10. INDA - alder fertilization indicator variable

   0 = alder fertilization has <u>not</u> occurred

   1 = alder fertilization <u>has</u> occurred

   - this indicator variable is reset, at TNOW + alder rotation length, in INDICAT

11. INDA2 - second alder fertilization indicator variable

0 = the previous rotation was a Douglas-fir one; uptakes rates are at normal levels

1 = the previous rotation was a red alder one; increase uptake rates accordingly

- INDA2 is not reset for the remainder of the simulated time