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POTASSIUM CYCLING IN COLORADO FORESTS.

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THESIS

SOIL DESCRIPTIONS AND SIMULATION MODEL OF POTASSIUM CYCLING IN COLORADO FORESTS

Submitted by

Robert George Woodmansee

In partial fulfillment of the requirements

for the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

August, 1972

COLORADO STATE UNIVERSITY

August, 1972

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY ROBERT GEORGE WOODMANSEE ENTITLED "SOIL DESCRIPTIONS AND SIMULATION MODEL OF POTASSIUM CYCLING IN COLORADO FORESTS" BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate Work

John Reuss

K. S. Doxtader

R M Hansen

Adviser

C R Reid

George Innis

C. Wayne Cook

Head of Department

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ABSTRACT OF THESIS

SOIL DESCRIPTIONS AND SIMULATION MODEL OF

POTASSIUM CYCLING IN COLORADO FORESTS

Soils under mature stands of Pinus contorta, Pseudotsuga menziesii, and Picea engelmanii-Abies lasiocarpa, were described and analyzed for certain chemical properties and variability. Potassium and carbon were used in the development of a simulation model of forest growth and potassium dynamics.

Profile characteristics recorded were color, texture, structure, consistence, thickness, stoniness, and content of roots. Chemical properties analyzed were pH, organic carbon, nitrogen, cation exchange capacity, phosphorus and exchangeable calcium, magnesium, potassium, and sodium. Carbon-nitrogen ratios and percentages of base saturation were calculated.

All soil horizons exhibited low fertility as expected in forest soils. The forest floor and surface mineral horizon in the Pseudotsuga menziesii stand contained unexpectedly high concentrations of calcium.

In general, the soils under Pinus contorta were least variable and those under Picea engelmanii-Abies lasiocarpa were most variable. Coefficients of variation for soil reactions were usually less than 10% while some exchangeable bases had coefficients near 100%. If sampling procedures were used to insure that sample means would fall within 10% of the true mean with 95% confidence the required number of samples from the B2 horizon, for example, would be 1, 31, 36, 36, 41, 85, 113, 35, and 18 for pH, C, N, C/N ratios, Ca, Mg, K, C.E.C.,

and percent base saturation, respectively, in the Pinus contorta stand, and in the Picea engelmanii-Abies lasiocarpa stand 1, 60, 82, 14, 698, 585, 626, 106, and 585 samples, respectively, would be required. Values in the Pseudotsuga menziesii stand were generally intermediate.

The simulation model utilized the SIMCOMP computer language developed in the U.S.I.B.P. Grassland Biome Program at Colorado State University. The forest simulated was assumed to be a pulse-stable, fire-maintained system resembling the Pinus contorta stand described in this study. The system was adjusted so inputs of nutrient via weathering and the atmosphere balanced outputs via leaching and erosion over a fire/growth cycle of 70 years, the assumed average frequency of fires.

This balanced system was then perturbed by two different clear-cutting practice simulations. One clearcut practice simulated removal of the boles of trees and the scattering of slash which was left to decompose as litter. At the end of three cutting cycles of 210 years total biomass of plants was 13% smaller than the comparable stage in the fire-maintained system. Potassium losses from the system were 15 to 20% of the total nutrient capital.

The other clearcut practice simulated bole removal and complete removal of slash from the system. This exercise of the model resulted in a 20% reduction in total biomass of plants and a 42% decrease in the potassium capital of the system.

Robert G. Woodmansee
Range Science Department
Colorado State University
Fort Collins, Colorado 80521
August, 1972

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I wish to thank Dr. W. H. Moir for his guidance in initiating this study and useful suggestions throughout. I thank Dr. R. M. Hansen for assuming the chairmanship of my graduate committee upon the departure of Dr. Moir from Colorado State University.

I gratefully acknowledge Dr. George S. Innis for his assistance in the modelling effort and Drs. K. G. Doxtader, J. O. Reuss, and C. P. P. Reid for their valuable suggestions throughout the duration of my graduate studies.

I wish to thank Mr. A. J. Cline for his assistance in classifying the soils according to the new system of nomenclature and his verifications of soil profile designations.

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INTRODUCTION

This manuscript reports a study of profiles, selected chemical properties and variability of soils and an analysis of data using a simulation model of forest growth and potassium (K) cycling in the lodgepole pine (Pinus contorta Dougl. var. latifolia Engelm.) vegetation type in the Front Range of Colorado in Boulder County. The study was initiated to collect data necessary for development of a nutrient cycling model of a typical lodgepole pine forest. The importance of studies of soils in formulating such models is suggested by Ovington (1962) and Rodin and Bazelivich (1967) for forests throughout the world, Duvigneaud and Denaeyer-De Smet (1970) for forests in Europe, and Cole and Gessel (1968), Likens et al. (1967), and Woodwell and Whittaker (1967) for forests in the United States. The magnitude of the nutrient capital of the soil, the rooting characteristics of plants, and erosion potential are only a few of the soil parameters which affect forest growth and nutrient cycling in forest ecosystems.

The model reported is a first attempt at synthesis of these data on soils and data of forest biomass and forest floors collected by W. H. Moir and others (Moir 1969 and 1972; Moir and Grier 1969; Moir and Francis 1972). The specific objective of the modeling exercise was to define and quantify some of the assumptions made by Curry (1970) and others (Subcommittee on Public Lands 1972) who suggested clearcutting may cause depletion of nutrients in forest ecosystems in the Intermountain West.

Vegetation

The sites studied were in stands of lodgepole pine, spruce-fir (Picea engelmanii (Parry) Engelm.-Abies lasiocarpa (Hook.) Nutt.) and Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco).

Moir (1969), Moir and Grier (1969) and Marr (1961) described the general topographic, climatic, edaphic, and vegetational features of the lodgepole pine zone of the Front Range of Colorado. Their emphasis was on areas in the Roosevelt National Forest in Boulder County. The three sites I studied are also in the same area and represent maximal forest variation within the type. The lodgepole pine site is Stand 1-1 of Moir and Grier (1969). The spruce-fir site is at the upper extent of the lodgepole pine zone in which lodgepole pine would be seral, and the Douglas-fir site is at the lower extent of the pine zone where a few remnant trees of a former lodgepole pine stand still remain.

Lodgepole Pine

The lodgepole pine site is located about 14 km south-southwest of Boulder (Latitude 39° 57' 45" N, Longitude 105° 26' 00" W). The elevation is 2690 m.

The sampling site is located on an upland, east-facing slope of 8 percent. The rock strata underlying the solum is precambrian Boulder Creek granite. The parent material immediately below the solum is composed of highly weathered rock which can be crushed easily by hand. This rock would rank in hardness classes seven or eight as described by Madole (1969, p 283).

The vegetation is essentially pure, even-aged, closed canopied lodgepole pine and is in the Pinus contorta/Geranium fremontii habitat type (Moir 1969). Average dbh (diameter at breast height, approximately 1.37 m) of the trees in 1966 was 0.70 dm with the largest 1.3 dm and the smallest 0.2 dm. Average age was 65 years with a range of 58 to 68 years. The average height was 9.1 m.

The total cover of understory vegetation is 0 percent but the following species occur in the stand: Rosa sp., Arctostaphylos uva-ursi, Populus tremuloides, Pyrola virens, Solidago spp., Penstemon virens, Corallorhiza spp., and Geranium fremontii (Moir 1969).

Douglas-Fir

The Douglas-fir site is located about 8 km west of Boulder (Latitude 39° 59' 00" N, Longitude 105° 22' 30" W). The elevation is 2560 m.

The site is located on a mid-canyon, north-facing slope of about 50 percent. The underlying material is similar to that of the lodgepole pine stand.

This vegetational type is in the Pseudotsuga menziesii/Jamesia americana habitat type (Daubenmire and Daubenmire 1968). In addition to Douglas-fir (94 percent) and lodgepole pine (2 percent) Pinus ponderosa (4 percent) occurs in this stand. Douglas-fir occurs in all dbh size classes from seedlings to 2.0 to 3.0 dm. The two pine species occur as mature trees and have no seedling representatives. This site was heavily logged about the turn of the 20th century.

Understory shrubs are Jamesia americana, the dominant (18 percent cover), and Arctostaphylus uvi-ursi, Juniperus communis, Physocarpus monogynus, Symphoricarpos albus, Acer glabrum, Shepherdia canadensis and Rosa sp. (totaling 4 percent cover). A large variety of herbs account for 3 percent of the ground cover. They include Arnica cordifolia, Carex rosii, Clematis ligusticifolia, Fragaria ovalis, F. americana, Lupinus argenteus, Potentilla fissa, Smilacina racemosa, Pyrola secunda, P. virens, Chimaphila umbellata, Arabis nudicaulis, Calypso bulbosa, Disporum trachycarpum, Senecio wootoni, Solidago spathulata, and Bromus sp. Cryptogams include Hypnum spp., Peltigera sp., and Parmelia conspersa (See Appendix A).

Spruce-Fir

The spruce-fir stand is located about 400 m east of the outlet of Brainard Lake in the south Saint Vrain Canyon (Latitude 40° 04' 30" N, Longitude 105° 34' 00" W). The elevation is 3380 m.

The location of the site is on a recessional moraine on the canyon floor with a south-southeast facing exposure of 1 to 4 percent slope. The material underlying the forest floor is glacial till of the middle stade of the Pinedale Glaciation (Madole 1969).

The site is in the Picea engelmanii-Abies lasiocarpa/Vaccinium myrtillus habitat type (Daubenmire and Daubenmire 1968). Both spruce and fir have representatives in all size classes from seedlings to 4.0 dm dbh (Unpublished data of W. H. Moir). The oldest tree sampled was 318 years old in 1966. All other age classes were represented demonstrating a typical uneven-aged, virgin spruce-fir forest.

Coverage by understory plants is essentially 100 percent. Of this total Vaccinium myrtilus (73 percent) is the dominant and mosses including Hypnum spp. (18 percent), lichens including Cladonia spp. (14 percent) and Peltigera sp. and unknown grasses comprise the remainder (See Appendix A).

METHODS

Sampling of mineral soils under the lodgepole pine, Douglas-fir, and spruce-fir stands was accomplished near Boulder, Colorado during the summer of 1970. One plot (about 50 m x 50 m) was located within the lodgepole pine and spruce-fir stands and two plots in the Douglas-fir stand where vegetation and the forest floor were visually judged to be representative of the stand type. The Douglas-fir 2 stand expresses greater coverage by understory vegetation and contains more numerous boulders which restricted sampling below 40 to 45 cm. It is also slightly steeper and is more mesic than Douglas-fir 1. Soil pits were located to represent maximum variability within the plot, also as visually judged using tree placement, understory vegetation, and the appearance of forest floor material as basic criteria. In the lodgepole pine and Douglas-fir 1 stands, six pits of approximately 1.0 m x 1.5 m were dug to a depth sufficient to expose the upper portion of the C horizon of the soil profile. In the Douglas-fir 2 stand five 0.5 m x 0.5 m pits were dug to a depth where boulders were encountered. Twelve 0.5 m x 0.5 m pits were dug down to the C horizon in the spruce-fir stand.

Descriptions of horizon depth, thickness, boundary characteristics and variations, color (Munsell notation), texture, structure, consistence, presence of roots and abundance of boulders, stone, gravel, or chert were made in situ (Soil Survey Staff 1951, 1960).

Both ends of the pits in the lodgepole pine and Douglas-fir 1 stands were sampled independently. One profile per pit was sampled from the other soils. Samples of soils of at least 400 g were

taken from all horizons which were of sufficient thickness (about 2 cm) to yield uncontaminated specimens. Cobbles and stones were discarded and the remaining soil placed in plastic bags which were securely sealed. The samples were brought to the laboratory, removed from the plastic bags, and air dried for four days. Samples were weighed and seived through 2 mm mesh screen with care taken to fracture the dried clods but not the gravel. The < 2 mm samples were weighed and placed into plastic bags and sealed. Later the samples were homogenized and sub-samples of about 40 g were ground with a porcelain mortar and pestle to pass through a 0.53 mm mesh screen. This portion was homogenized and about 10 grams were subsampled and ground to pass through a 0.25 mm mesh screen. The 0.53 mm portion was used for analysis of easily oxidizable carbon by the Walkley-Black method (Allison 1965). The 0.25 mm material was used for nitrogen analysis by the semimicro-Kjeldahl method (Bremner 1965). The 2 mm portion was used for pH, exchangeable bases, cation exchange capacity, phosphorus, and texture analysis. Hydrogen ion activity was measured in a 1:1 soil-water ratio using a glass electrode. Exchangeable K, Na, Mg, and Ca ions were determined using the extraction procedures of Pratt (1965) with the modification of using three 33 ml washings instead of four 25 ml washings. C.E.C. (Cation Exchange Capacity) determinations followed the sodium saturation procedures of Chapman (1965). Atomic absorption spectrometry was used to determine Ca and Mg and flame photometry used for K and Na. Phosphorus determination followed the procedures of Watanabe and Olsen (1965). All samples collected were analyzed for pH, C, and N. The other chemical properties were analyzed from one profile in each pit. The hydrometer method

described by Day (1965) using overnight shaking for dispersion was used to determine particle size distribution from representative profiles.

The forest floor at the lodgepole pine site had been previously sampled and analyzed by Moir and Grier (1969). Forest floor material was sampled in the summer of 1971 in the Douglas-fir 1, Douglas-fir 2, and the spruce-fir sites by placing a 12.20 m transect in a representative location in each stand and taking eight 0.25 m^2 samples at 1.54 m intervals. Forest floor horizons within the 0.25 m^2 plot were not separated. The samples were prepared following, with slight modification, the procedures of Moir and Grier (1969). Loss-on-ignition values were determined by slowly heating 1.0 g of forest floor material to 600°C and maintaining it at that temperature for three hours. Nitrogen analysis was made by semimicro-Kjeldahl procedures (Bremmer 1965). A hydrochloric acid digestion was used to isolate P, Na, K, Mg, and Ca. Phosphorus was analyzed by the method of Watanabe and Olsen (1965), and Na and K by flame photometry and Mg and Ca by atomic absorption spectrophotometry.

All values are reported on an oven-dry basis. Duplicate samples were run every five to ten determinations to insure validity of the techniques.

The simulation model was constructed utilizing the SIMCOMP version 2.0 computer programming system developed at Colorado State University by Gustafson and Innis (1972).

RESULTS AND DISCUSSION

Soils

Only two detailed soil surveys are available for the mountains of Colorado; the Fraser Alpine Area (Retzer 1962) and the Trout Creek Watershed (Retzer 1961). Johnson and Cline (1965) described the morphology of several typical profiles of montane soils in Colorado but details are wanting. Brief morphological characteristics of soils from the Front Range of Colorado have been given in Moir (1969) and Madole (1969). Moir and Grier (1969) described, in detail, the forest floors under several lodgepole pine stands.

Lodgepole Pine

Two typical soil profiles were classified according to the Soil Survey Staff (1960, 1965, and 1968) as follows (See Appendix B):

Profile A - Typic Cryoboralf - coarse-loamy, mixed family

Profile B - Typic Cryoboralf - fine-loamy, mixed family

Rock outcrops are the dominant features causing variations in soil depth and profile expression. Important changes in profile characteristics often occur within a few decimeters horizontal distance. For example, at this site, one pit revealed a well defined Gray Wooded soil at one end while the other was an A/C lithosol. Stones and fallen logs frequently are encountered which contribute to variability.

The O1 and O2 horizons are well differentiated and 2 to 4 cm thick. Moir and Grier (1969) give descriptions of these layers in L, F, and H terminology.

The A1 horizon is continuous, 2 to 5 cm thick with dry colors that range from very dark brown to dark grayish brown. The dark colors are due, in part, to charcoal which is common. A narrow, broken color B2 horizon, called the A21 in Profile A, sometimes underlies the A1 and may represent bisequal development. Occasionally a bisequal A2 can be found between the A1 and bisequal B2 but it is no greater than 2 or 3 mm thick. A concentration of cobbles is noted in this horizon.

A thick (20-40 cm) A2 horizon is well expressed and often can be differentiated into distinct subhorizons. Dry colors range from brown to light yellowish brown. The large majority of roots occur in the upper two master horizons. The transition horizons A3 and B1 are commonly observed.

The B2 horizons vary from strongly developed as in Profile B to weakly developed (Profile A) where differentiation from A2, B, and C material is difficult. Dry colors vary from hues 5 YR to 10 YR with values of five or six and chromas from four to eight. The colors of some inclusions and bands are found on the 2.5 YR hue sheet. Clay accumulation may be slight as seen in Profile A or obvious as in Profile B. Some of the small inclusions and bands show the only tendency for structure in any of the horizons. This structure is weak subangular blocky.

A B3 transition horizon is often distinguishable but differentiation between it and the C horizon is often arbitrary.

Douglas-fir

Two typical profiles were described for Douglas-fir 1 to illustrate the extreme variability over short distances. Only one profile

was needed to represent Douglas-fir 2. The Douglas-fir 1 soils were classified according to the Soil Survey Staff (1960, 1965, 1968) as follows (See Appendix B):

Douglas-fir 1

Profile A - Dystric Cryochrept - coarse-loamy, mixed family

Profile B - Typic Cryoboralf - coarse-loamy, mixed family

Solum depth is 30 to 88 cm. Horizon expression is poor in most profiles but is well expressed in some.

Discontinuities in the forest floor are caused by numerous boulders, small drainage channels, fallen logs, and the wide variety of understory plants. Most pits were located where coniferous debris was the primary component of the litter material and was continuous except for the protruding boulders. The litter material tends to accumulate around boulders and understory plants. Deer and elk droppings occur sporadically. The depth of the forest floor ranges from 2 to 10 cm.

Stones and cobbles, decaying wood from fallen stems and roots, charcoal, and irregular occurrences of massive quantities of living roots and fungal hyphae help explain the extreme variability in the A1 horizon. Decayed root channels are common causing irregular drainage patterns and downward extensions of the horizon. The A1 generally is 2 to 6 cm thick but may be 12 cm thick and irregular where root channels or stones are present. The dry colors range from black to dark grayish brown.

Cobbles and stones occupy up to 75 to 80 percent of the A2 horizon causing extreme irregularity. The A2 material may extend downward 30 cm. Where the cobbles and stones occupy only 5 to 10

percent of the A2 horizon, it is usually less than 10 cm thick. The dry color ranges from dark brown to pale brown. Indistinct A3 and B1 transition horizons may underlie the A2 horizon.

The B2 horizons range from well developed with distinct subhorizons (Profile B) and overall depth of 35 to 50 cm to poorly developed (Profile A) where differentiation between A2, B2, and C is possible only through chemical analysis. The poorly developed horizons are only 20 to 25 cm thick. When a well developed horizon occurs a subhorizon of clay accumulation generally occurs. Dry colors range from hues 7.5 YR to 10 YR with values 5 and 6 and chromas 3 to 8. The presence of cobbles and stones does not appear to greatly influence development of this horizon.

Differentiation between B3 and C horizons is difficult if not impossible.

The Douglas-fir 2 soil was classified according to the Soil Survey Staff (1960, 1965, 1968) as a Dystric Cryochrept sandy-skeletal, mixed family (See Appendix B).

Forest floor material and mineral soils can accumulate only between and in depressions caused by boulders and hence are broken and discontinuous. Only small pits could be dug between the boulders. Soil material was extracted from between boulders and in small cracks.

The plant debris constituting the forest floor is an admixture of the overstory and understory species, including decaying wood. Its depth ranges from 4 to 7 cm. Distinct horizonation is evident in the forest floor but precise differentiation between the 02 and A1 horizons is difficult due to considerable mixing of humus and

mineral material. The 02 and much of the A1 horizons are bound together by an extensive root-mycelia network.

The A1 horizon is very dark brown to black due, in part, to charcoal. The horizon ranges from 3 to 10 cm thick. There is some evidence in the form of narrow bands (1 or 2 mm thick) of grayish brown material of bisequal profile development similar to but less extensive than that described for the lodgepole pine soils. Some horizons can be separated into two distinct subhorizons.

The A2 horizon generally expresses two or three subhorizons but precise differentiation is often difficult. Differentiation between the A2 and B2 horizons is also difficult. In all pits the solum terminated at subsurface boulders. The dry colors vary from dark yellowish brown to light brownish gray. Numerous roots are present in all horizons examined.

Spruce-fir

Two profiles were described to illustrate variability. Both profiles represented common occurrences (See Appendix B).

The soils are classified according to the Soil Survey Staff (1960, 1965, 1968) as Typic Cryoboralf fine-loamy, mixed family.

The forest floor in the spruce-fir forest is a mosaic of rock in and on the solum, fallen decaying logs and varying concentrations of understory vegetation. Fallen trees have caused considerable churning of the soils by uprooting. These factors cause irregularity and extreme contrasts within short distances. The forest floor may be 10 to 20 cm thick at one point and only a few decimeters away may be non-existant. Where the forest floor exists, roots, mosses,

lichens, and mycelia often form an inseparable conglomerate combined with dead plant material and the upper surface of the mineral soil. The depth of the solum is relatively uniform and ranges from 35 to 48 cm thick.

Occasionally a very weak A1 horizon occurs but the common mineral horizon at the surface is a strongly developed A2 that often can be divided into subhorizons. This horizon ranges for < 1 to 10 cm thick, is irregular, and sometimes broken. Its color is typical of albic horizons with dry colors being hue 10 YR, values 5 to 7 and chromas 2 or 3. It contains numerous roots and cobbles and often contains stones of 0.5 m diameter or larger.

Generally there is an abrupt or clear transition between the A2 to B2 horizons. The B2 is commonly divided into subhorizons and ranges in thickness from 25 to 35 cm. The upper subhorizon frequently expresses clay illuviation and a lower one a band expressing distinct clay accumulation. Most subhorizons contain narrow bands or inclusions of widely varying colors and texture. However, the predominant colors are variations of yellowish brown with the subhorizons of clay accumulation being brown.

The lower strata of the B horizon is often a B3 transition horizon and along with the C horizon expresses extreme mottling.

Chemical Analysis

Forest Floor

Certain chemical properties of the forest floors under the Douglas-fir and spruce-fir stands were analyzed (Table 1). Moir and Grier (1969) presented similar data from the lodgepole pine stand 1-1. The lodgepole pine data was subdivided by subhorizons and includes the Ail stratum of the mineral soil. My data are for the intact forest floor with no subdivision of horizons and they do not include the surface mineral subhorizon.

The weights of forest floor humus, corrected for ash residues as suggested by Moir and Grier (1969), in the spruce-fir and both Douglas-fir stands were about twice as great as values found in the lodgepole pine stand. These differences were due, primarily, to the greater amounts of decaying wood in the forest floors of the first three sites. McFee and Stone (1966) discussed the implications of wood fragments in forest soils and concluded wood is slowly decomposed. Variability of humus weight was so large within the Douglas-fir 1, Douglas-fir 2, and spruce-fir sites that comparisons between stands were not made.

The mean values for the weights of the forest floor material under the Douglas-fir 1 and Douglas-fir 2 stands were similar to the lower end of the ranges reported by Youngberg (1966) for Douglas-fir stands in western Oregon. However, the climatic environments in Colorado and Oregon are so different that comparisons may be meaningless.

Table 1. Selected chemical properties of the forest floors in the Douglas-fir and Spruce-Fir stands. Measures of central tendency, dispersion, number of samples (n) used to calculate measures and the number of samples (N) required to place estimated mean within 10% of the true mean with 95% confidence

Chemical Characteristics and Stand	Mean	Median	Standard Deviation	Coefficient of Variation	Confidence Interval (95%)	Range	n	N
Humus ($g.25\ m^{-2}$)								
Lodgepole pine*	693						7	
Douglas-fir 1	1712	1659	653	38	$1165 \leq \mu \leq 2259$	543-2647	8	105
Douglas-fir 2	1257	1230	662	53	$703 \leq \mu \leq 1811$	311-2250	8	158
Spruce-Fir	1425	1312	560	39	$956 \leq \mu \leq 1894$	661-2255	8	86
Ash (%)								
Lodgepole pine*								
Douglas-fir 1	36.1	35.2	6.5	18	$30.7 \leq \mu \leq 41.5$	28.3-49.2	8	18
Douglas-fir 2	41.1	40.8	8.7	21	$33.8 \leq \mu \leq 48.4$	28.7-51.0	8	25
Spruce-Fir	30.2	29.5	8.8	29	$22.8 \leq \mu \leq 37.6$	18.2-40.9	8	47
Nitrogen (%)								
Lodgepole pine*	1.22					1.08-1.40	7	
Douglas-fir 1	0.80	0.81	0.14	17	$0.64 \leq \mu \leq 0.96$	0.61-1.01	8	17
Douglas-fir 2	0.93	0.92	0.14	15	$0.81 \leq \mu \leq 1.05$	0.84-1.14	8	13
Spruce-Fir	1.00	1.03	0.14	14	$0.89 \leq \mu \leq 1.11$	0.82-1.22	8	11
Phosphorus (%)								
Lodgepole pine*	0.11					0.07-0.14	7	
Douglas-fir 1	0.075	0.075	0.008	11	$0.068 \leq \mu \leq 0.082$	0.068-0.085	8	8
Douglas-fir 2	0.075	0.073	0.006	8	$0.070 \leq \mu \leq 0.080$	0.069-0.083	8	4
Spruce-Fir	0.076	0.079	0.012	15	$0.066 \leq \mu \leq 0.086$	0.059-0.088	8	13
Potassium (%)								
Lodgepole pine*	0.3					0.3-0.5	7	
Douglas-fir 1	0.075	0.073	0.019	26	$0.060 \leq \mu \leq 0.090$	0.054-0.111	8	39
Douglas-fir 2	0.082	0.078	0.011	14	$0.073 \leq \mu \leq 0.091$	0.069-0.104	8	11
Spruce-Fir	0.074	0.075	0.010	14	$0.064 \leq \mu \leq 0.082$	0.060-0.089	8	11
Magnesium (%)								
Lodgepole pine*								
Douglas-fir 1	0.108	0.104	0.013	12	$0.097 \leq \mu \leq 0.119$	0.086-0.126	8	9
Douglas-fir 2	0.138	0.141	0.027	19	$0.115 \leq \mu \leq 0.161$	0.016-0.151	8	21
Spruce-Fir	0.114	0.117	0.021	19	$0.097 \leq \mu \leq 0.131$	0.079-0.139	8	21
Calcium (%)								
Lodgepole pine*	0.4					0.3-0.6	7	
Douglas-fir 1	1.312	1.286	0.207	16	$1.139 \leq \mu \leq 1.485$	1.088-1.738	8	15
Douglas-fir 2	1.703	1.657	0.332	20	$1.425 \leq \mu \leq 1.981$	1.288-2.125	8	23
Spruce-Fir	0.755	0.738	0.137	18	$0.640 \leq \mu \leq 0.870$	0.556-0.975	8	18
Sodium (%)								
Lodgepole pine*								
Douglas-fir 1	0.020	0.019	0.005	27	$0.015 \leq \mu \leq 0.025$	0.016-0.029	8	41
Douglas-fir 2	0.021	0.021	0.003	14	$0.018 \leq \mu \leq 0.024$	0.016-0.026	8	11
Spruce-Fir	0.016	0.015	0.004	27	$0.012 \leq \mu \leq 0.020$	0.012-0.023	8	41

*After Moir and Grier (1969).

The ash percentages reflected the type of humus present with the spruce-fir forest floor representing a mor type (distinct transition between humus layers and mineral soil) with a lesser amount of mixing of mineral with organic material. The Douglas-fir soils displayed a mull type humus (gradual transition between humus and mineral soil) with greater mixing of mineral and organic material. These data are not directly comparable to the data of Moir and Grier (1969) since their forest floor material was subdivided.

The percentages of P in the spruce-fir and Douglas-fir stands were lower than those in the lodgepole pine stand. The Douglas-fir values were lower than those found in the northwest by Youngberg (1966) reflecting lower fertility of soils in the Central Rocky Mountain Region.

Nitrogen percentages compared favorably with those in the lodgepole pine stand and Douglas-fir stands in Oregon suggesting the consistancy of C/N ratios in plant material.

Potassium percentages in the three stands reported were smaller than those found in the lodgepole pine stand (Table 1). This may have been due to more effective leaching caused by more precipitation in the spruce-fir stand or more effective precipitation caused by the north-facing exposure of the Douglas-fir stands. Another possibility is that understory plants present in the spruce-fir and Douglas-fir stands were more efficient in removing K from the lower strata of the forest floor than were the pines.

The K values for the Douglas-fir stands were at the lower end of the ranges reported for K in Youngberg (1966) and again reflect lower soil fertility.

The percentage of Mg was not reported by Moir and Grier (1969). The values found in my study were similar for all three stands. The Douglas-fir Mg values were again lower than in the Oregon stands suggesting this too contributes to the low fertility classification of Colorado forest soils.

Sodium values were very low in the spruce-fir and Douglas-fir stands suggesting the element is very mobile (Wilde 1958). Sodium values were not reported by Youngberg (1966) nor Moir and Grier (1969).

Calcium percentages were higher in the spruce-fir stand than in the lodgepole pine stand, but the values for both of these sites were much lower than the Douglas-fir sites. The high concentrations in the latter were also reflected in the mineral soils and will be discussed below. These high values were brought about by the high concentrations of Ca in Douglas-fir litter material (Daubenmire 1953). These values were also higher than those found by Youngberg (1966). This was possibly due to less efficient leaching resulting from less rainfall than occurs in Oregon.

Mineral Soil

Certain chemical properties and percentages of clay in the mineral soils of all three vegetation types were analyzed (Table 2).

Soils at the lodgepole pine site were very strongly acid in the surface mineral horizons and increased in pH to medium acid with increasing depth as Lutz and Chandler (1946) and Ovington (1953) suggested should be expected. The pH values in the spruce-fir soils followed the same trend, increasing from extremely acid to very

Table 2. Selected chemical properties of the mineral soils.

Horizon	Depth	pH	Total C	N	Base Satr.	Exchangeable Cations Ca	Mg	K	CEC	P	C/N	% Clay
	cm.		%			meq/100g				ppm		
					Lodgepole Pine A							
A11	0- 3	5.1	2.76	0.087	26	3.43	1.01	0.39	13.4	12.5	31.6	6
A21	3- 5	5.2	1.01	0.030	27	2.31	0.63	0.21	10.2	26.5	33.8	5
A22	5-22	5.5	0.75	0.033	37	3.31	0.90	0.21	9.4	32.3	22.9	7
A & B	22-53	5.8	0.19	0.026	36	2.93	0.75	0.14	16.4	19.8	7.3	6
B2t	53-79	5.8	0.21	0.029	47	5.18	1.49	0.24	16.4	31.3	7.4	12
C	79+	5.8	0.12	0.019	66	9.67	2.84	0.24	11.8	24.8	7.0	10
					Lodgepole Pine B							
A1	0- 4	4.8	2.73	0.073	43	6.67	1.54	0.53	20.4	15.0	37.4	7
A21	4-19	5.1	0.55	0.027	30	2.62	0.49	0.14	11.0	16.3	20.2	7
A22	19-34	5.5	0.19	0.016	34	2.87	0.60	0.14	10.6	17.5	11.7	7
B21t	34-43	5.6	0.26	0.027	59	9.98	3.74	0.53	24.2	42.5	9.5	21
B22t	43-68	5.6	0.14	0.014	77	8.11	3.17	0.42	15.2	42.5	9.8	20
B3	68-89	5.8	0.09	0.009	--	8.54	3.33	0.39	----	35.3	10.4	20
C	89+	6.0	0.15	0.014	63	7.61	2.96	0.30	17.2	25.5	10.9	10
					Douglas-fir 1 A							
A1	0- 2	5.5	12.56	0.367	59	20.72	2.17	0.43	39.2	34.3	34.2	9
A2	2-10	5.0	0.96	0.039	37	3.95	0.83	0.20	13.6	40.5	24.4	7
A3	10-21	5.1	0.60	0.037	39	3.76	0.93	0.18	12.4	40.8	17.4	4
B1	21-43	4.9	0.22	0.015	38	3.58	0.97	0.20	12.4	30.0	14.7	4
B2	43-50	5.1	0.26	0.020	50	5.32	1.63	0.25	14.2	29.3	13.1	5
C	50+	5.4	0.23	0.026	58	6.73	2.32	0.30	16.0	30.0	8.8	-
					Douglas-fir 1 B							
A11	0- 4	6.5	9.30	0.379	73	22.46	1.75	0.53	34.0	48.0	24.5	8
A12	4- 6	---	----	-----	--	----	----	----	----	----	----	-
A2	6-15	4.5	0.63	0.035	25	2.56	0.66	0.21	13.6	56.0	18.0	4
A & B	15-56	5.3	0.80	0.059	20	3.51	0.77	0.18	22.0	40.5	13.5	3
B21t	56-62	5.2	0.30	0.022	35	5.42	2.39	0.24	22.8	26.5	13.6	5
B22t	62-81	5.4	0.14	0.015	45	4.12	1.88	0.18	13.6	17.0	9.3	6
B23t	81-91	5.4	0.16	0.016	63	7.55	4.69	0.35	20.0	29.3	10.0	16
C	91+	5.6	0.18	0.041	65	8.80	3.95	0.18	19.8	35.3	4.6	8
					Douglas-fir 2							
A1	0-11	5.4	2.35	0.077	55	8.23	1.05	0.30	17.4	46.8	30.7	5
A21	11-12	---	----	-----	--	----	----	----	----	----	----	-
A22	12-22	5.3	0.43	0.026	29	2.42	0.47	0.18	10.6	51.5	16.9	4
B2	22-41	5.2	0.43	0.020	27	2.20	0.47	0.18	10.6	61.0	21.2	4
					Spruce-Fir A							
A2	0- 5	3.9	2.71	0.109	22	2.93	0.94	0.28	18.8	21.3	25.0	10
B1	5-13	4.3	1.36	0.078	10	1.81	0.59	0.21	24.8	15.3	17.4	14
B21t	13-24	4.4	1.96	0.117	8	1.50	0.45	0.24	26.4	15.5	16.5	9
B22t	24-38	4.6	0.71	0.028	1	0.34	0.07	0.07	36.0	19.0	25.4	28
B3	38-48	4.9	0.62	0.041	2	0.36	0.06	0.07	22.0	21.0	15.1	9
C	48+	5.2	0.38	0.031	2	0.20	0.04	0.04	16.4	20.8	12.3	7
					Spruce-Fir B							
A2	0-12	3.8	1.89	0.094	11	1.37	0.38	0.10	16.4	10.3	20.1	6
B21t	12-20	4.4	2.00	0.102	5	0.81	0.48	0.10	26.4	33.0	19.6	22
B22	20-36	4.6	1.29	0.069	2	0.31	0.09	0.04	18.8	13.0	18.7	9
C	36+	4.6	0.26	0.028	2	0.25	0.04	0.04	14.8	13.8	9.3	6

strongly acid. The values I obtained for the spruce-fir soils were from 0.5 to 0.8 pH units lower than those reported by Retzer (1962) for podzols in the Frazer area, 15 to 20 miles distant but in a different range of mountains. Values in the A1 horizon of the Douglas-fir 1 soils ranged from strongly acid to slightly acid, reflecting the high base content, especially Ca, of the organic horizons and Douglas-fir needles (Daubenmire 1953). Buckman and Brady (1969) discussed the effect of Ca on soil pH and pointed out that, generally, hydrogen ion activity decreases when Ca ion activity increases. A decrease in pH to very strongly acid was noted in the A2 horizon and was related to the decrease in organic matter and exchangeable base content. The pH values increased with depth from strongly to medium acid below the A2 horizon. The Douglas-fir 1 pH profile resembled the moderately acid to strongly acid Gray Wooded soils of Johnson and Cline (1965). The Douglas-fir 2 profiles decreased in pH with depth but only to a modified extent when compared to Douglas-fir 1.

Carbon decreased with depth in the lodgepole pine, Douglas-fir 1 A, and Douglas-fir 2 soils. The other soils contained zones of accumulation of translocated humus in the upper portion of their B horizons. Carbon values, otherwise, compared favorably with the podzol and Gray Wooded soils of the Frazer (Retzer 1962) and Trout Creek (Retzer 1961) areas with the exception of the Douglas-fir 1 A1 horizons. In the latter, the extremely high carbon levels reflected the absence of well-defined 02 horizons in the forest floor due to greater mixing with the mineral material below.

Nitrogen values followed the same patterns as those of carbon. The generalization set forth by Hockensmith and Tucker (1933) that soil nitrogen increases with increasing elevation in the Front Range appeared to be substantiated by this study if B2 horizons are compared. Nitrogen values in the B2 horizon of the spruce-fir soils were higher than in the B2 horizons of the other soils.

Carbon-nitrogen ratios decreased with increasing depth as expected (Lutz and Chandler 1946). The ratios were lower on the eastern slope of the Front Range than in the Frazer (Retzer 1962) and Trout Creek (Retzer 1961) soils. This presumably resulted from temperatures being warmer than in the Frazer area and precipitation being more abundant than in the Trout Creek Watershed. I assume microbial activity is greater in the Front Range soils with resultant, more effective and complete decomposition of organic material.

Cation-exchange-capacities of various horizons showed different patterns of distribution than did the soils of the Frazer and Trout Creek areas (Retzer 1961, 1962). The differences result from the development of zones of accumulation of clay and humus colloids in many of the subsurface horizons of the Front Range soils. Increased C.E.C. appears to be mostly a function of accumulated humus in the B21t horizons of the Douglas-fir 1 B and spruce-fir A soils while the increase in the spruce-fir B B21t subhorizon is a function of both humus and clay colloids. C.E.C.'s correlate with clay colloids in the other horizons. Horizons of clay accumulation are non-existent in the Frazer Watershed soils except in the Tabernash loam soils (Retzer 1962).

The exchangeable bases showed the same patterns of distribution as the C.E.C. values, except in the spruce-fir soils where the bases decreased with depth regardless of the colloids present and in the Douglas-fir 2 soils where concentrations became constant. Sodium values were not reported explicitly because they were in the < 0.1 meq/100g range and most did not differ from blanks used in calibration.

The amount of exchangeable calcium in the lodgepole pine and spruce-fir soils was generally 2 to 4 times greater than exchangeable Mg and was 10 to 20 times greater than exchangeable K, for corresponding horizons. Exchangeable calcium content in the A1 horizons of the Douglas-fir soils was about 10 times greater than Mg and 50 times greater than K. The subsurface horizons of the Douglas-fir soils showed patterns similar to the lodgepole pine and spruce-fir soils.

The percentage of base saturation in all the soils was generally less than in other soils reported from Colorado mountains. These lower percentages were brought about by greater acidity. With the exception of the A1 horizons in the Douglas-fir soils and the lowermost horizons in the lodgepole pine and Douglas-fir 1 soils, the exchange complexes were less than one-half saturated. These horizons were the least acid of any of the surface horizons reported.

Phosphorus values expressed in part per million (ppm) can only be used here as relative measures since the method of determination is reliable only for neutral and slightly basic soils. The behavior of P was very erratic. The only generalization that can be made is that profiles which contain a clay accumulation in a subsurface horizon also exhibit a P accumulation in the same horizon.

The soils were of low fertility when compared to agricultural soils. Exchangeable potassium values were comparable to forest soils from other regions of North America (Ike and Clutter 1968; McFee and Stone 1965; Cole and Gassel 1968; and Retzer 1961, 1962). The quantities were uniformly low and the assumption is that the potassium which is not lost from the systems via leaching is in large part accumulated in living material (Likens et al. 1967 and Leaf 1968). Exchangeable calcium and magnesium values were comparable to values from other forests except those of humid regions where these two elements are leached out of the ecosystem to a greater extent. Nitrogen values were also similar to other forest systems and seemed to be correlated more with carbon values than climate.

Chemical Variation

Various measures of central tendency, dispersion, variability, and sample sizes required to insure that a sample mean will fall within 10 percent of a hypothesized true mean with 95 percent confidence were determined. The required sample size is a function of the coefficient of variation and was calculated by the formula $N = t\ (CV/\%\ error)$ where N = sample size required, t is the appropriate value from a table giving Student's - t distribution, CV is the coefficient of variation, and % error is the allowable variation from the mean.

Forest Floor

The variability of weights of humus material taken from the $0.25\ m^2$ quadrats was high with coefficients of variation of 38, 53,

and 39% for Douglas-fir 1, Douglas-fir 2, and the spruce-fir stands, respectively (Table 1). Moir and Grier (1969) found the coefficients of variation in the lodgepole pine stand were 15% indicating a much more uniform distribution of litter material. The causes of the greater variability in the forest floors and mineral soils of the Douglas-fir and spruce-fir stands are discussed in detail in the next section.

The variation in percentage of ash was relatively lower in the Douglas-fir stands than in the spruce-fir stand (Table 1). The greater variation in the latter was partly due to the inevitable contamination of samples with mineral material brought about by the intermingling of the roots of Vaccinium myrtillus and mosses with litter material. Moir and Grier (1969) gave no measures of variation for ash material in the lodgepole pine forest floor.

The coefficients of variation for the nutrients in the forest floor were all low when compared to mineral soils except for Na which is of little importance as discussed in this paper (Table 1). The low values resulted from the relative uniformity of plant material when compared to mineral soil material. The forest floor, especially the upper horizons, is greatly influenced by the plant material above and less influenced by the pedogenic processes occurring below. With increasing depth these influences reverse.

No distinguishable patterns of variation of forest floor nutrients can be abstracted from the data.

Mineral Soil

Comparisons were made between those horizons which were judged to best represent the master horizons of the solum. Selection was made on this basis because not all horizons and subhorizons were represented in all profiles. Where master horizons were non-existent no allowance was made such as adding zero values for the missing horizon.

Both parametric and non-parametric tests were used to describe the data. In general, both techniques agreed.

Separate samples from both ends of the soil pits in the lodgepole pine and Douglas-fir 1 were analyzed for pH, C, and N. Both Kendall's rank correlation and standard analysis of variance tests (Sokal and Rohlf 1969) showed that within-pit values in the lodgepole pine soils could be considered independent while the values in the Douglas-fir 1 were shown to be highly correlated and not independent. As a result of these tests all values were used to calculate parameters in the lodgepole pine soils. For the Douglas-fir soils, only values from the sides of the pits which were represented with complete sets of data were considered.

Low coefficients of variation were found for pH values resulting in only a few samples being required to estimate the means in all stands (Table 3). One pit would be adequate in the lodgepole pine soils. Variability remained constant or decreased with depth in all soils. When compared with other characteristics sampled, these low coefficients may be misleading. Ike and Clutter (1968) pointed out that pH values are logrithmic measurements while the

other values are linear resulting in possible inappropriate comparisons of variability.

Carbon values (Table 4) varied widely both within stands and within profiles. The surface mineral horizons in the lodgepole pine and Douglas-fir soils varied least presumably due to the more uniform composition of the litter material above. The reader should keep in mind that the spruce-fir soils have no A1 horizon. The variability within the A2 horizons of the lodgepole pine and Douglas-fir 1 soils increased but decreased in the Douglas-fir 2 soils. The variation within the B2 horizons decreased in the lodgepole pine, Douglas-fir 2 and spruce-fir soils but increased in the Douglas-fir 1 soil. Variations in both C and N in the spruce-fir soils studied here were similar to those found in a New York podzol studied by McFee and Stone (1965).

Variation in nitrogen values (Table 5) increased with depth in the lodgepole pine stand, decreased in Douglas-fir 2, and remained the same in the spruce-fir stand. In the Douglas-fir 1 stand soil variation decreased in the A2 horizon but increased again in the B2 horizon. These results poignantly illustrate the lack of comparability of the soils from the different sites.

In general, the carbon/nitrogen ratios (Table 6) had smaller coefficients of variation especially in surface horizons of the Douglas-fir 1 and the spruce-fir soils, than either carbon or nitrogen alone. This suggests a close relationship between C and N in a given horizon.

The exchangeable bases, Ca, Mg, and K (Tables 7, 8 and 9) varied greatly, both within and between horizons, the only exception

being the A2 horizon of the lodgepole pine soil. The coefficients of variation were enormous by comparison in the B2 horizon of the spruce-fir soils. Coefficients for Ca were comparable to those found by Ike and Clutter (1968) but my values for K were much higher than theirs.

Cation-exchange-capacities (Table 10) varied somewhat less than exchangeable bases in most profiles. Variability was high in the A1 and B2 horizons and lower in the A2 indicating lower and more consistant contents of colloids in the latter. Variation in the Douglas-fir 2 soils was nearly constant throughout the profile.

The percentages of base saturation (Table 11) showed no distinguishable patterns of variation except that values were high in the spruce-fir soils.

Variability of phosphorus showed a distinct pattern in the lodgepole pine and Douglas-fir 1 soils (Table 12). Values were moderate in the surface horizons, dropped noticeably in the A2 horizons, and rose sharply in the B2 horizons. The low variability of the A2 horizons resulted from the low and more consistant percentages of mineral clay present since the negatively charged phosphate ions were assumed to be positively absorbed by clay particles (Fried and Broeshart 1967). The greater variability in the B2 horizons resulted from the greater quantities and greater variability of clays present. Variation in the Douglas-fir 2 soils was nearly constant reflecting more consistent quantities of clay. Variation in the spruce-fir soils was high and reverses the expected pattern.

The overall variability was lowest in the lodgepole pine stand reflecting the greater uniformity of the overstory vegetation and

lack of understory plants. Judging from the charcoal present, fire has had a unifying influence on this stand. Except for pH determination, the numbers of replicates required to develop statistically precise estimators was still large. The number of replicates required in the other soils were up to a magnitude higher than values in the lodgepole pine soils. All chemical characteristics considered, variability was highest in the spruce-fir soils reflecting a long-term undisturbed condition of the forest with resultant increased complexity of the structure of the forest floor. The variation may relate primarily to fallen logs in all stages of decomposition and churning of the soil caused by upturned root systems of fallen trees. In addition, the soils were younger at this site and according to Harridine (1949) the variability could be expected to be greater. The greatest sources of variation in both Douglas-fir soils were probably due to the presence of large stones and boulders and complexity of the understory vegetation.

Where comparisons were appropriate the results from my study agreed reasonably well with those of Mader (1963), Frankland et al. (1963), McFee and Stone (1965), Metz et al. (1966), Ike and Clutter (1968) and Usher (1970). All authors agree that statistically precise sampling is infeasible due to the cost, time and amount of labor required in collection and analysis.

Not considered in my study are sizeable temporal variations mentioned by Frankland et al. (1963) and Usher (1970).

At least some mention should be made regarding bias introduced into my study as well as those mentioned previously. Study sites were generally selected in stands that were most representative

and homogeneous. Pits were dug in subplots that represented maximum environmental gradients within a given site. Also, I avoided digging pits within 1 to 2 meters of trees. According to Zinke (1962) this would mean I did not sample the lowest pH values or the highest nitrogen and exchangeable bases values. Further, studies should be conducted to determine the affects of these introduced bias' on studies of forest soils.

Owing to the extreme variability within pits and with the same stand, and variability between stands, any generalizations about the availability and distribution of nutrients in or the morphology of these Front Range soils must be confined to particular sites.

The soils were so variable within stands that large numbers of samples required analysis before precise estimates of soil parameters can be achieved. Precise sampling requires large investments of time and labor because the soils generally are so rocky that sampling must be accomplished by digging soil pits rather than taking soil cores.

Research entailing sampling of soils in different vegetative stands should be discouraged unless an adequate number of soil samples can be taken to establish reasonable sample means. Often ecological studies are undertaken in which vegetation is analyzed and one soil core or pit is sampled and regarded as representative. The results of my data strongly emphasize the inadequacy of such procedures.

Forest soils are dynamic, living systems and great variability should not be considered as an undesirable trait or a characteristic to be corrected. The variability is a very important and meaningful

Table 3. Hydrogen Ion Activity (pH). Measures of central tendency, dispersion, number of samples (n) used to calculate measures, and number of samples (N) required to place estimated mean within 10% of the true mean with 95% confidence in the mineral soils.

Stand and Horizon	Mean	Median	Standard Deviation	Coefficient of Variation	Confidence Interval (95%)	Range	n	N
Lodgepole Pine								
A1	5.0	5.1	0.3	6	$4.8 \leq \mu \leq 5.2$	4.3-5.5	12	2
A2	5.4	5.3	0.3	6	$5.2 \leq \mu \leq 5.6$	4.8-5.9	12	2
B2	5.7	5.7	0.2	4	$5.5 \leq \mu \leq 5.9$	5.4-6.0	8	1
Douglas - fir 1								
A1	6.1	6.2	0.4	6	$5.7 \leq \mu \leq 6.5$	5.5-6.5	6	3
A2	5.0	5.1	0.3	6	$4.7 \leq \mu \leq 5.3$	4.5-5.3	6	3
B2	5.2	5.3	0.3	5	$4.9 \leq \mu \leq 5.5$	4.8-5.5	6	2
Douglas - fir 2								
A1	5.7	5.6	0.4	7	$5.2 \leq \mu \leq 6.2$	5.4-6.4	5	4
A2	5.4	5.3	0.2	4	$5.1 \leq \mu \leq 5.7$	5.1-5.7	5	2
B2	5.4	5.4	0.2	3	$5.2 \leq \mu \leq 5.6$	5.2-5.6	5	1
Spruce-Fir								
A2	3.9	3.9	0.2	5	$3.7 \leq \mu \leq 5.1$	3.7-4.3	10	2
B2	4.4	4.4	0.2	4	$4.3 \leq \mu \leq 4.5$	4.1-4.7	12	1

Table 4. Carbon (% oven-dry weight). Measures of central tendency, dispersion, number of samples (n) used to calculate measures, and number of samples (N) required to place estimated mean within 10% of the true mean with 95% confidence in the mineral soils.

Stand and Horizon	Mean	Median	Standard Deviation	Coefficient of Variation	Confidence Interval (95%)	Range	n	N
Lodgepole Pine								
A1	3.20	3.29	0.70	22	$2.76 \leq \mu \leq 3.64$	2.02-4.53	12	24
A2	0.28	0.22	0.12	43	$0.20 \leq \mu \leq 0.36$	0.15-0.50	12	90
B2	0.23	0.23	0.06	25	$0.18 \leq \mu \leq 0.28$	0.16-0.35	8	31
Douglas - fir 1								
A1	9.59	9.53	1.66	17	$7.85 \leq \mu \leq 11.33$	7.42-12.38	6	19
A2	0.73	0.62	0.33	45	$0.38 \leq \mu \leq 1.08$	0.46-1.39	6	134
B2	0.36	0.28	0.20	56	$0.15 \leq \mu \leq 0.57$	0.15-0.64	6	207
Douglas - fir 2								
A1	4.72	2.71	3.37	71	$0.54 \leq \mu \leq 8.90$	2.05-9.99	5	390
A2	1.24	1.12	0.79	64	$0.26 \leq \mu \leq 2.22$	0.43-2.21	5	317
B2	0.53	0.51	0.12	23	$0.38 \leq \mu \leq 0.68$	0.43-0.73	5	41
Spruce-Fir								
A2	2.73	2.23	1.74	64	$1.19 \leq \mu \leq 4.25$	0.82-6.40	10	210
B2	1.66	1.61	0.54	35	$1.32 \leq \mu \leq 2.00$	0.71-2.51	12	60

Table 5. Nitrogen (% oven-dry weight). Measures of central tendency, dispersion, number of samples (n) used to calculate measures, and number of samples (N) required to place estimated mean within 10% of the true mean with 95% confidence in the mineral soils.

Stand and Horizon	Mean	Median	Standard Deviation	Coefficient of Variation	Confidence Interval (95%)	Range	n	N
Lodgepole Pine								
A1	0.097	0.095	0.018	19	$0.085 \leq \mu \leq 0.109$	0.073-0.133	11	18
A2	0.026	0.024	0.006	23	$0.022 \leq \mu \leq 0.030$	0.019-0.041	12	26
B2	0.023	0.023	0.006	26	$0.018 \leq \mu \leq 0.028$	0.016-0.030	8	36
Douglas - fir 1								
A1	0.301	0.333	0.117	39	$0.178 \leq \mu \leq 0.424$	0.107-0.424	6	101
A2	0.047	0.051	0.014	30	$0.032 \leq \mu \leq 0.062$	0.035-0.069	6	60
B2	0.025	0.022	0.010	42	$0.015 \leq \mu \leq 0.035$	0.013-0.044	6	103
Douglas - fir 2								
A1	0.158	0.116	0.110	70	$0.021 \leq \mu \leq 0.295$	0.077-0.340	5	379
A2	0.047	0.051	0.017	39	$0.023 \leq \mu \leq 0.067$	0.026-0.064	5	118
B2	0.025	0.021	0.001	29	$0.016 \leq \mu \leq 0.034$	0.017-0.033	5	65
Spruce - Fir								
A2	0.106	0.103	0.043	41	$0.053 \leq \mu \leq 0.159$	0.062-0.177	5	128
B2	0.083	0.098	0.034	41	$0.061 \leq \mu \leq 0.105$	0.028-0.118	12	82

Table 6. Carbon Nitrogen Ratio. Measures of central tendency, dispersion, number of samples (n) used to calculate measures, and number of samples (N) required to place estimated mean within 10% of the true mean with 95% confidence in the mineral soils.

Stand and Horizon	Mean	Median	Standard Deviation	Coefficient of Variation	Confidence Interval (95%)	Range	n	N
Lodgepole Pine								
A1	34.1	33.8	2.0	6	$32.7 \leq \mu \leq 35.5$	31.6-37.9	11	2
A2	11.4	11.0	4.3	38	$8.7 \leq \mu \leq 14.1$	5.1-17.8	12	70
B2	9.9	8.9	2.5	25	$7.8 \leq \mu \leq 12.0$	7.4-13.5	8	36
Douglas - fir 1								
A1	28.7	27.0	5.9	20	$22.6 \leq \mu \leq 34.8$	22.6-37.1	6	27
A2	16.0	16.6	5.1	32	$11.7 \leq \mu \leq 21.3$	8.8-23.6	6	68
B2	14.2	13.4	5.1	36	$8.9 \leq \mu \leq 19.5$	6.8-22.1	6	86
Douglas - fir 2								
A1	29.4	28.6	3.9	13	$23.3 \leq \mu \leq 35.5$	26.1-34.2	4	18
A2	25.6	21.8	8.8	34	$14.6 \leq \mu \leq 36.6$	16.9-39.4	5	90
B2	22.3	21.9	5.9	26	$15.0 \leq \mu \leq 29.6$	14.0-30.2	5	53
Spruce - Fir								
A2	22.4	22.9	5.1	23	$16.1 \leq \mu \leq 28.7$	15.1-29.1	5	41
B2	19.5	20.4	3.3	17	$17.4 \leq \mu \leq 21.6$	11.4-22.6	12	14

Table 7. Calcium (meg 100 g soil^{-1}). Measures of central tendency, dispersion, number of samples (n) used to calculate measures, and number of samples (N) required to place estimated mean within 10% of the true mean with 95% confidence in the mineral soils.

Stand and Horizon	Mean	Median	Standard Deviation	Coefficient of Variation	Confidence Interval (95%)	Range	n	N
Lodgepole Pine								
A1	5.4	5.6	1.7	32	$3.5 \leq \mu \leq 6.3$	3.4-7.2	6	68
A2	2.9	2.9	0.3	9	$2.6 \leq \mu \leq 3.2$	2.6-3.2	6	6
B2	7.6	8.3	1.8	23	$5.6 \leq \mu \leq 10.2$	5.2-10.0	5	41
Douglas - fir 1								
A1	21.1	22.8	7.3	35	$13.4 \leq \mu \leq 28.8$	7.3-29.0	6	81
A2	4.0	3.3	1.8	44	$2.1 \leq \mu \leq 5.9$	2.6-7.2	6	128
B2	6.2	5.4	2.6	42	$3.5 \leq \mu \leq 8.9$	3.1-10.6	6	117
Douglas - fir 2								
A1	11.6	8.7	6.8	59	$3.2 \leq \mu \leq 20.0$	5.4-22.8	5	269
A2	3.6	4.5	1.4	39	$1.9 \leq \mu \leq 5.3$	1.8-4.8	5	118
B2	2.5	2.5	0.4	17	$2.0 \leq \mu \leq 3.0$	2.0-3.0	5	23
Spruce-Fir								
A2	2.1	1.4	1.3	61	$0.5 \leq \mu \leq 3.7$	0.9-3.8	5	288
B2	1.4	0.8	1.3	95	$<0 \leq \mu \leq 3.0$	0.3-3.4	5	698

Table 8. Magnesium (meg 100 g soil^{-1}). Measures of central tendency, dispersion, number of samples (n) used to calculate measures, and number of samples (N) required to place estimated mean within 10% of the true mean with 95% confidence in the mineral soils.

Stand and Horizon	Mean	Median	Standard Deviation	Coefficient of Variation	Confidence Interval (95%)	Range	n	N
Lodgepole Pine								
A1	1.2	1.0	0.4	33	$0.8 \leq \mu \leq 1.6$	0.7-1.7	6	72
A2	0.7	0.7	0.2	22	$0.5 \leq \mu \leq 0.9$	0.5-0.9	6	32
B2	2.5	2.4	0.8	33	$1.5 \leq \mu \leq 3.5$	1.5-3.7	5	85
Douglas - fir 1								
A1	2.1	2.0	0.8	39	$1.3 \leq \mu \leq 2.9$	0.8-3.2	6	101
A2	0.8	0.7	0.3	41	$0.5 \leq \mu \leq 1.1$	0.5-1.4	6	111
B2	1.7	2.0	0.9	51	$0.8 \leq \mu \leq 2.6$	0.5-2.6	6	172
Douglas - fir 2								
A1	1.3	1.1	0.4	29	$0.8 \leq \mu \leq 1.8$	1.0-1.9	5	65
A2	0.6	0.7	0.2	26	$0.4 \leq \mu \leq 0.8$	0.4-0.8	5	53
B2	0.5	0.5	0.1	26	$0.3 \leq \mu \leq 0.7$	0.4-0.7	5	53
Spruce - Fir								
A2	0.6	0.4	0.4	57	$0.1 \leq \mu \leq 1.1$	0.4-1.2	5	251
B2	0.5	0.5	0.4	87	$0.0 \leq \mu \leq 1.0$	0.1-1.1	5	585

Table 9. Potassium (meg 100 g soil^{-1}). Measures of central tendency, dispersion, number of samples (n) used to calculate measures and number of samples (N) required to place estimated mean within 10% of the true mean with 95% confidence in the mineral soils.

Stand and Horizon	Mean	Median	Standard Deviation	Coefficient of Variation	Confidence Interval (95%)	Range	n	N
Lodgepole Pine								
A1	0.4	0.4	0.1	29	$0.2 \leq \mu \leq 0.5$	0.2-0.5	6	51
A2	0.1	0.1	0.0	11	$\mu = 0.1$	0.1-0.2		
					$(0.12 \leq \mu \leq 0.16)$	(0.12-0.016)	6	8
B2	0.3	0.3	0.1	38	$0.2 \leq \mu \leq 0.5$	0.2-0.5	5	112
Douglas - fir 1								
A1	0.5	0.5	0.1	25	$0.4 \leq \mu \leq 0.7$	0.4-0.80	6	42
A2	0.2	0.2	0.1	24	$0.1 \leq \mu \leq 0.3$	0.2-0.3	6	38
B2	0.2	0.2	0.0	11	$0.2 \leq \mu \leq 0.3$	0.2-0.3	6	8
					$(0.20 \leq \mu \leq 0.26)$	(0.20-0.27)		
Douglas - fir 2								
A1	0.5	0.5	0.2	42	$0.3 \leq \mu \leq 0.70$	0.3-0.8	5	137
A2	0.4	0.4	0.1	38	$0.2 \leq \mu \leq 0.6$	0.2-0.5	5	112
B2	0.3	0.3	0.1	36	$0.2 \leq \mu \leq 0.4$	0.2-0.5	5	101
Spruce - Fir								
A2	0.2	0.1	0.1	60	$0.1 \leq \mu \leq 0.3$	0.1-0.3	5	279
					$(0.04 \leq \mu \leq 0.27)$	(0.07-0.28)		
B2	0.2	0.1	0.0	90	$<0 \leq \mu \leq 0.4$	0.1-0.4	5	626
					$(0 \leq \mu \leq 0.34)$	(0.07-0.42)		

Table 10. Cation Exchange Capacity (meg 100 g soil^{-1}). Measures of central tendency, dispersion, number of samples (n) used to calculate measures, and number of samples (N) required to place estimated mean within 10% of the true mean with 95% confidence in the mineral soils.

Stand and Horizon	Mean	Median	Standard Deviation	Coefficient of Variation	Confidence Interval (95%)	Range	n	N
Lodgepole Pine								
A1	18.1	17.5	3.7	20	$14.2 \leq \mu \leq 22.0$	13.4-23.8	5	27
A2	10.7	10.6	0.8	7	$9.9 \leq \mu \leq 11.5$	9.4-11.8	6	4
B2	17.6	16.4	3.8	21	$12.9 \leq \mu \leq 22.3$	14.8-24.2	5	35
Douglas - fir 1								
A1	34.0	39.2	11.0	32	$20.4 \leq \mu \leq 47.6$	15.0-42.0	6	80
A2	12.6	12.7	2.4	19	$10.1 \leq \mu \leq 15.1$	8.6-16.0	6	24
B2	16.0	14.9	4.2	29	$11.6 \leq \mu \leq 20.4$	12.0-22.8	6	45
Douglas - fir 2								
A1	21.6	17.4	9.1	42	$10.3 \leq \mu \leq 32.9$	13.6-36.9	5	137
A2	16.6	14.6	6.3	38	$8.3 \leq \mu \leq 24.4$	10.6-26.4	5	112
B2	14.4	11.0	5.6	39	$7.4 \leq \mu \leq 21.4$	10.6-23.6	5	118
Spruce - Fir								
A2	17.5	18.8	2.1	12	$14.9 \leq \mu \leq 20.1$	14.4-19.2	5	12
B2	23.6	24.8	8.8	37	$12.7 \leq \mu \leq 34.5$	13.6-36.0	5	106

Table 11. Base Saturation (%). Measures of central tendency, dispersion, number of samples (n) used to calculate measures, and number of samples (N) required to place estimated mean within 10% of the true mean with 95% confidence in the mineral soils.

Stand and Horizon	Mean	Median	Standard Deviation	Coefficient of Variation	Confidence Interval (95%)	Range	n	N
Lodgepole Pine								
A1	39	38	9	24	$29 \leq \mu \leq 49$	26-54	6	39
A2	39	36	9	22	$30 \leq \mu \leq 47$	31-55	6	32
B2	61	60	9	15	$49 \leq \mu \leq 73$	47-72	5	18
Douglas - fir 1								
A1	68	69	9	14	$56 \leq \mu \leq 80$	57-78	5	16
A2	39	41	11	28	$27 \leq \mu \leq 51$	25-55	6	52
B2	51	50	16	31	$34 \leq \mu \leq 68$	32-69	6	63
Douglas - fir 2								
A1	62	56	14	22	$45 \leq \mu \leq 79$	48-82	5	38
A2	31	31	14	44	$14 \leq \mu \leq 48$	10-47	5	150
B2	25	27	9	35	$14 \leq \mu \leq 36$	12-35	5	95
Spruce - Fir								
A2	16	11	8	50	$6 \leq \mu \leq 26$	10-27	5	194
B2	9	5	8	87	$<0 \leq \mu \leq 19$	1-20	5	585

Table 12. Phosphorus (ppm). Measures of central tendency, dispersion, number of samples (n) used to calculate measures, and number of samples (N) required to place estimated mean within 10% of the true mean with 95% confidence in the mineral soils.

Stand and Horizon	Mean	Median	Standard Deviation	Coefficient of Variation	Confidence Interval (95%)	Range	n	N
Lodgepole Pine								
A1	14.0	13.9	3.7	26	$11.6 \leq \mu \leq 16.4$	8.8-23.6	12	33
A2	17.5	17.9	2.6	13	$15.9 \leq \mu \leq 19.1$	13.8-19.6	12	9
B2	29.0	30.7	10.1	35	$20.5 \leq \mu \leq 37.5$	12.3-42.5	8	69
Douglas - fir 1								
A1	47.6	46.3	9.5	20	$37.6 \leq \mu \leq 57.6$	34.3-61.0	6	26
A2	48.6	46.9	7.1	15	$41.2 \leq \mu \leq 56.0$	40.8-58.0	6	15
B2	34.9	31.2	13.3	38	$20.9 \leq \mu \leq 48.9$	19.0-54.0	6	96
Douglas - fir 2								
A1	53.8	52.8	10.1	19	$41.3 \leq \mu \leq 66.3$	44.0-70.0	5	28
A2	56.5	51.5	11.7	21	$42.0 \leq \mu \leq 71.0$	43.5-70.5	5	34
B2	50.5	46.8	11.3	22	$36.5 \leq \mu \leq 64.5$	38.3-63.8	5	38
Spruce - Fir								
A2	14.4	12.9	7.8	54	$8.8 \leq \mu \leq 20.0$	5.5-25.5	10	149
B2	19.4	15.6	9.9	51	$13.1 \leq \mu \leq 25.7$	8.0-44.3	12	126

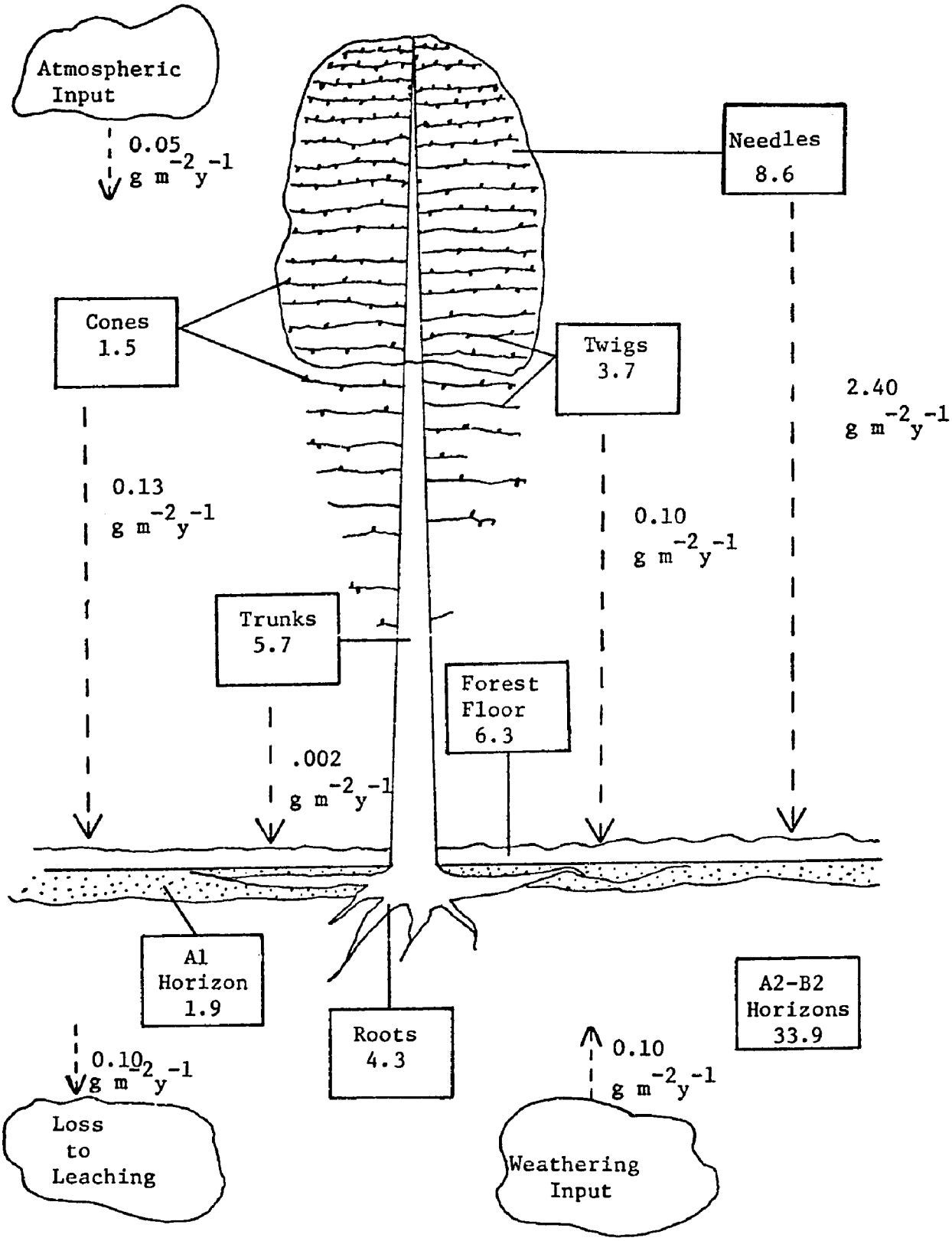
property of biological communities. Speculation about the ecological significance of these highly varying systems is not the purpose of this paper but the implications are many and varied.

Potassium Cycling in a Lodgepole Pine Forest

The objective of the modeling effort was to study the dynamics of forest growth and the dynamics of net-annual K (potassium) cycling in a representative lodgepole pine forest in the Colorado Front Range. The model focuses on the lodgepole pine stand described in this manuscript. Potassium was chosen for study because of its importance as a growth limiting cation in species of forest trees (Likens et al. 1967 and Leaf 1968) and because data on this element was more complete and reliable than data for other elements considered (Fig. 1). The model produced is general and will allow the inclusion of other nutrients as data becomes available. The model developed represents a synthesis of data on soils presented in this manuscript, unpublished work done by Dr. W. H. Moir, the literature, and the modeling expertise of Dr. George S. Innis. The model presented is the first working version, thus it is preliminary. Many of the values taken from the literature are real and appear to be reasonable but may not be the best values available. Further development will entail 1) searching the literature for better data and 2) exercising the model to determine sensitivity to parameters and responsiveness to manipulation of variables.

The hypothesis examined stated the potassium capital of a lodgepole pine ecosystem would be depleted if clearcutting techniques are utilized at time intervals sufficient to allow growth of trees

Figure 1. Potassium status of a lodgepole pine ecosystem during year 70 of a burn growth cycle. Numbers in the boxes are g m^{-2}.


Atmospheric Input
0.05 g m^{-2}y^{-1}
Needles 8.6
Cones 1.5
Twigs 3.7
2.40 g m^{-2}y^{-1}
0.13 g m^{-2}y^{-1}
0.10 g m^{-2}y^{-1}
Trunks 5.7
Forest Floor 6.3
.002 g m^{-2}y^{-1}
A1 Horizon 1.9
A2-B2 Horizons 33.9
Roots 4.3
0.10 g m^{-2}y^{-1}
0.10 g m^{-2}y^{-1}
Loss to Leaching
Weathering Input

to harvestable size in normal systems. Three perturbations were chosen to be examined with the simulation technique; 1) three-regularly-occurring wildfire and forest recovery cycles, 2) three-regularly-occurring clearcutting cycles in which boles are harvested and slash is raked into small piles and burned, and 3) three-regularly-occurring clearcutting cycles in which boles are harvested but slash is left to decompose in situ. The wildfire simulation represents the natural system and is used as a control against which the clear cut systems are compared.

All systems assume natural or man-aided reproduction but no fertilization.

Likens et al. (1967) argued that nutrient budgets in climax forest ecosystems must balance over long periods of time. Likens et al. (1970) and others affirmed that in natural, unmanaged, true-climax forests annual nutrient inputs do nearly equal annual nutrient losses. This type of system may be expressed arithmatically as follows:

$$Wi + Pi = NEo + NLo \qquad \text{(Equation 1)}$$

where

Wi = nutrient released by chemical weathering of soil parent material

Pi = input of nutrients via precipitation, dust, and other atmospheric sources

NEo = steady-state erosion losses

NLo = steady-state leaching losses

and all other inputs and outputs are assumed negligible.

The argument must be modified to explain nutrient budgets in vegetation types like lodgepole pine whose natural existence depends on holocaust. These systems must be considered pulse-stable (Odum 1971) with budgets balancing over long-term growth cycles rather than annually. Within an average cycle of forest growth, following establishment of sufficient plant cover to prevent erosion and retard accelerated leaching losses, annual inputs of nutrients into the system via weathering and the atmosphere must exceed annual losses. The following arithmatic argument represents this assertion for an average burn-growth cycle:

$$Wi + Pi = NE_o + NL_o + AE_o + AL_o \qquad \text{(Equation 2)}$$

where Wi, Pi, NE_o, and NL_o are defined as in Equation 1

AE_o = Accelerated erosion due to fire

AL_o = Accelerated leaching caused by fire

and all other inputs and outputs are assumed negligible.

Development of the above argument requires an estimate of the time scale of a burn-growth cycle. There are no data suggesting the average frequency of fires in the Colorado Mountains. However, Leiberg (1900) suggested fires were frequent in the 200 years previous to the onslaught of white men. Clements (1910) traced the fire history near Estes Park, Colorado and found burning to be frequent. Heinselman (1970) found that fires were frequent and might have an average frequency of 5 to 50 years in some areas and 200 to 300 years in other areas of Minnesota. Using these subjective data a value of 70 years was chosen to represent the average frequency of

fires in the lodgepole pine type upon which this study is based. This value coincides with the approximate age of the lodgepole pine stand in which our data were collected. The 70 year value was also selected to represent the clearcut-growth cycles.

Based upon these assumptions and addressing the objective of this exercise directly, the model was developed to simulate growth of; 1) a fire maintained sub-climax forest in which growth of forest biomass and total nutrients in the ecosystem achieve cyclic stability and, 2) two forests that had received different clearcut treatments.

Implementation

The SIMCOMP language described in Technical Report 138 of the U.S.I.B.P. Grassland Biome Series (Gustafson and Innis 1972) was used to implement the model. The listing of the model (fire maintained system) which appears in Appendix D and in the next section would be difficult to interpret without an understanding of SIMCOMP. The reader is directed to Technical Report 138 for further information and definitions of terms.

Model Structure

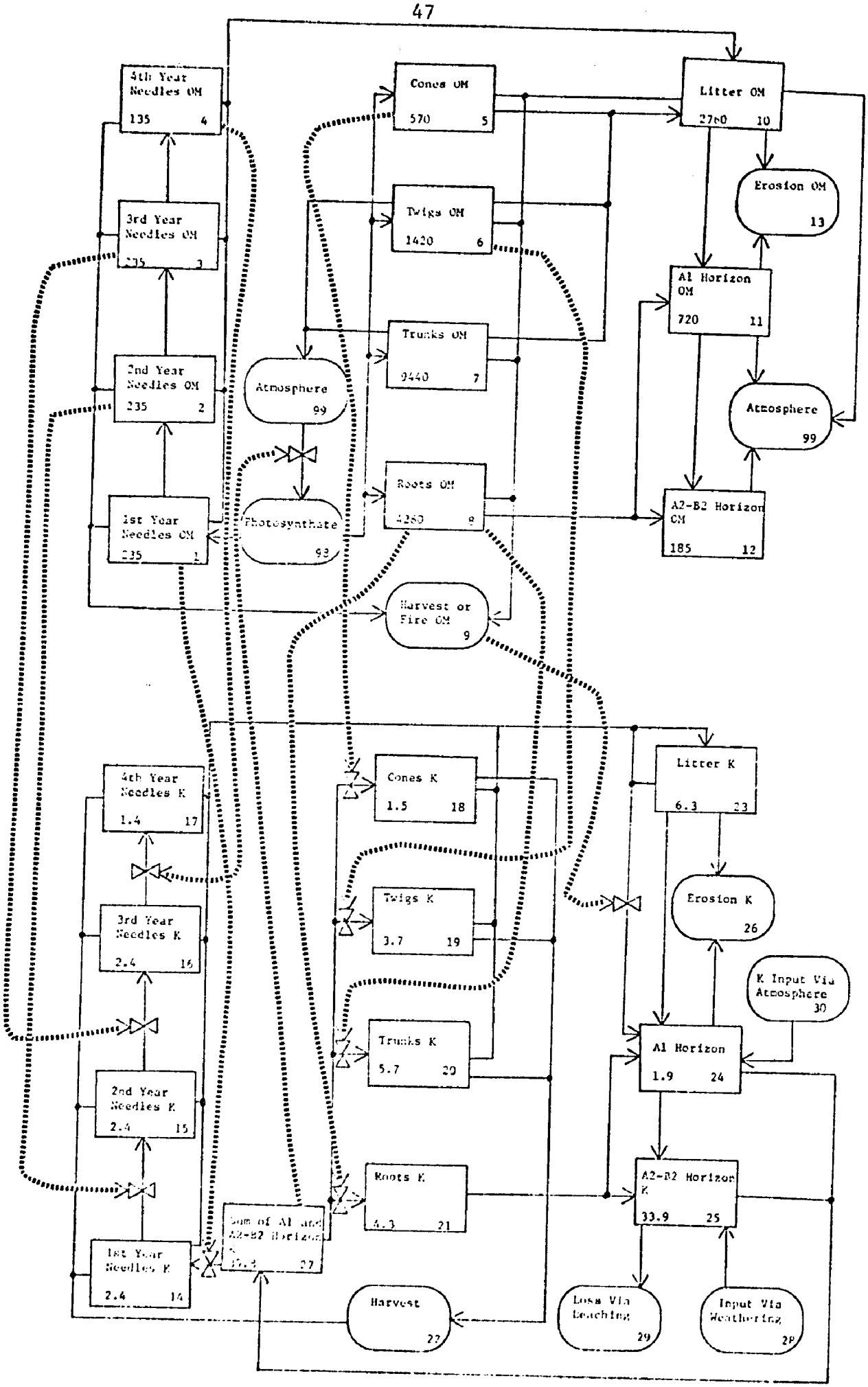
Two submodels were developed to accomplish the simulations (Fig. 2):

1. A biomass submodel to follow the growth of the forest and,
2. A potassium submodel which is directly linked to the former.

The boxes in the flow diagram are read as follows:

1. At the top of the box is a word or words defining the contents of the compartment,

Figure 2. Flow diagram for the simulation model of forest growth and potassium cycling in a lodgepole pine ecosystem. Values in the lower left corners of the boxes are in $g\ m^{-2}$ and represent the estimated quantities of organic matter (OM) or potassium (K) in a 70 year old forest.


4th Year Needles OM
135 4
3rd Year Needles OM
235 3
2nd Year Needles OM
235 2
1st Year Needles OM
235 1
Cones OM
570 5
Twigs OM
1420 6
Trunks OM
9440 7
Roots OM
4260 8
Atmosphere
99
Photosynthate
93
Harvest or Fire OM
9
Litter OM
2760 10
Erosion OM
13
A1 Horizon OM
720 11
Atmosphere
99
A2-B2 Horizon OM
185 12
4th Year Needles K
1.4 17
3rd Year Needles K
2.4 16
2nd Year Needles K
2.4 15
1st Year Needles K
2.4 14
Cones K
1.5 18
Twigs K
3.7 19
Trunks K
5.7 20
Roots K
4.3 21
Sum of A1 and A2-B2 Horizons
27
Harvest
27
Litter K
6.3 23
Erosion K
26
K Input Via Atmosphere
30
A1 Horizon
1.9 24
A2-B2 Horizon K
33.9 25
Loss Via Leaching
29
Input Via Weathering
28

2. The number designating the box is given in the lower right-hand corner, and
3. The number in the lower left-hand corner of the box is the measured or estimated value of the contents (g m^{-2}) of the component at a stand age of about 70 years and represents the steady-state conditions of the model (Appendix C).

The non-rectangular shapes are sinks or pools of material and are read in the same manner as the boxes except that measured or estimated values are not shown.

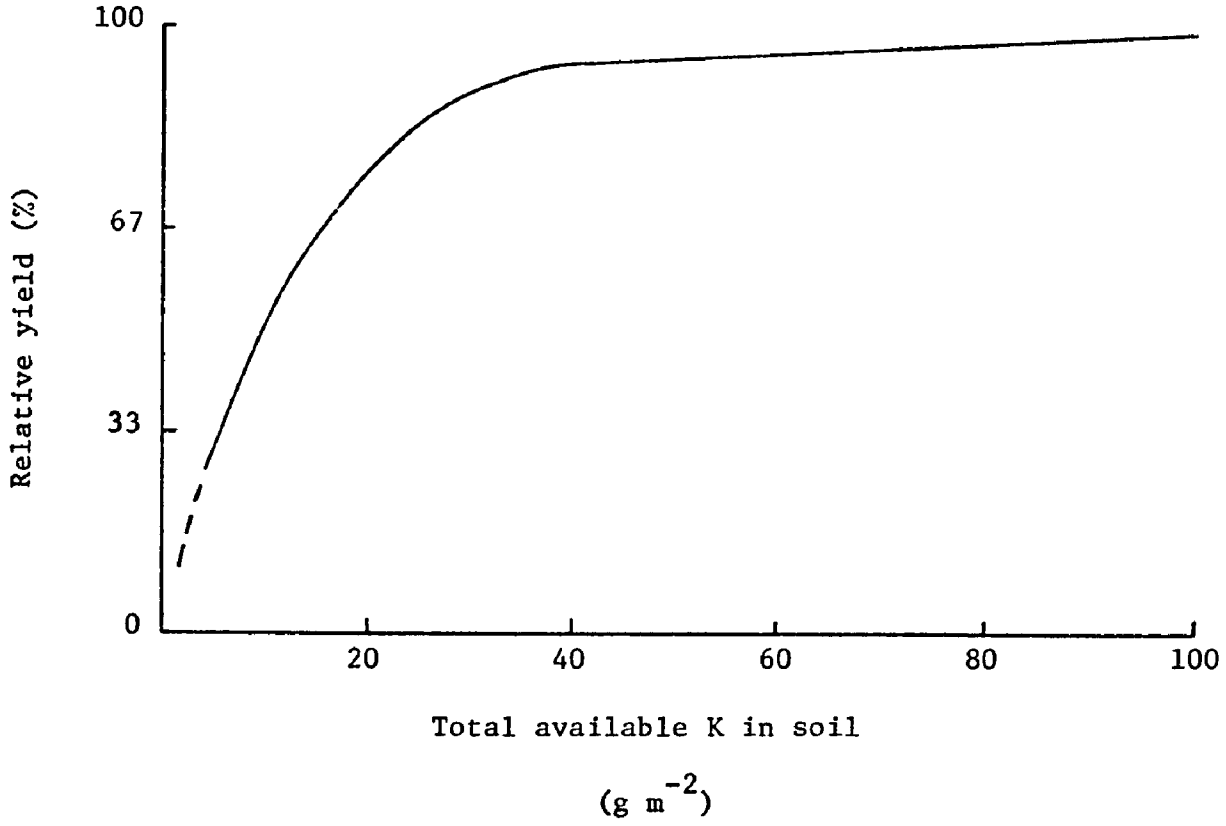
Flows of material between compartments are represented by solid arrows and are read from a compartment to a compartment or as (i, j) where i is the donor compartment and j is the receiver compartment.

The dashed arrows leading to the inverted, paired triangles (valves) represent the flow of information rather than material. The valves control the flow of material.

The flows will be discussed in detail below but a general description of the dynamics of the biomass-nutrient model should be helpful now.

Carbon in the form of atmospheric CO_2 is fixed by the needles as photosynthate and is translocated upon growth demand to actively growing tissues in needles, cones, twigs, trunks, and roots. The translocated organic matter is fixed as perennial tissue; is oxidized back to the atmosphere via respiration or fire; or returned to the litter or mineral soil where it is ultimately respired to the atmosphere by microbial activity. Organic matter can also be removed from the system by harvest.

Figure 3. Idealized yield-response curve relating photosynthate production to available K in the soil. (After Black 1968).


100
67
33
0
Relative yield (%)
20
40
60
80
100
Total available K in soil
(g m^{-2})

The driving variable in this model is photosynthate which is generated from growth curves found in the literature (Rodin and Bazelivich 1967). Values for maximum photosynthate production are assumed for non-nutrient limited systems. These maximum values are then multiplied by correction factors representing nutrient-limited growth. These are taken from a generalized nutrient response curve (Fig. 3). The potassium response curve in this model results from evaluation of the soil nutrient pool (X_{24} and X_{25}).

Potassium enters and leaves the system as suggested in Equation 2 in addition to potential loss by harvest. Available K in the soil can be absorbed by the plant tissues upon demand of increased biomass of various organs. A portion of K in the needles is assumed to be organically bound (not available for loss by leaching). Thus concentrations of K in the standing crop organs are assumed to remain constant. Potassium returns to the litter or mineral soil following death and abcission. The element is removed from the dead material either by microbial decomposition or leaching.

Only the net annual flux of nutrient is considered. Intra-seasonal leaching and exudation from living plant material and consequent re-absorption was not considered because; 1) the concern of the modeling effort was the long-term dynamics of the system (hundreds of years); 2) the rapid cycling and translocation of K (Kozlowski 1971) would require short (monthly or less) time steps which are not justified by the current knowledge of the system or the model objectives.

Derivation of the Model

The heart of a dynamic systems model is the flow of material from one compartment to another and the controls which operate on those flows. Of equal importance in the modeling effort is the rationale used to develop the flows and controls. To execute flows, initial values for the components are necessary in addition to values for all of the parameters. These values are presented in Appendix E for each perturbation.

In the discussion which follows, the pair of numbers included in the parentheses at the right-hand margin refer to the flow under consideration. Following this pair of numbers is the description of the flow from the first compartment to the second. All flows pictured in Fig. 2 will be discussed whether or not this version of the model actually includes the flow. Examples of this latter case are where flows are implied as in (99, 98) and not actually calculated in the program, added in initial conditions as in (8, 9), or calculated in a subroutine as in (24, 27). The order of discussion of the flows, where possible, will be from compartment to compartment with all inputs and outputs for each component covered before proceeding to the next compartment.

(99, 98).

FLOW DEFINITION: Amount of organic matter that flows into the photosynthate pool as CO_2.

SIMCOMP code: none

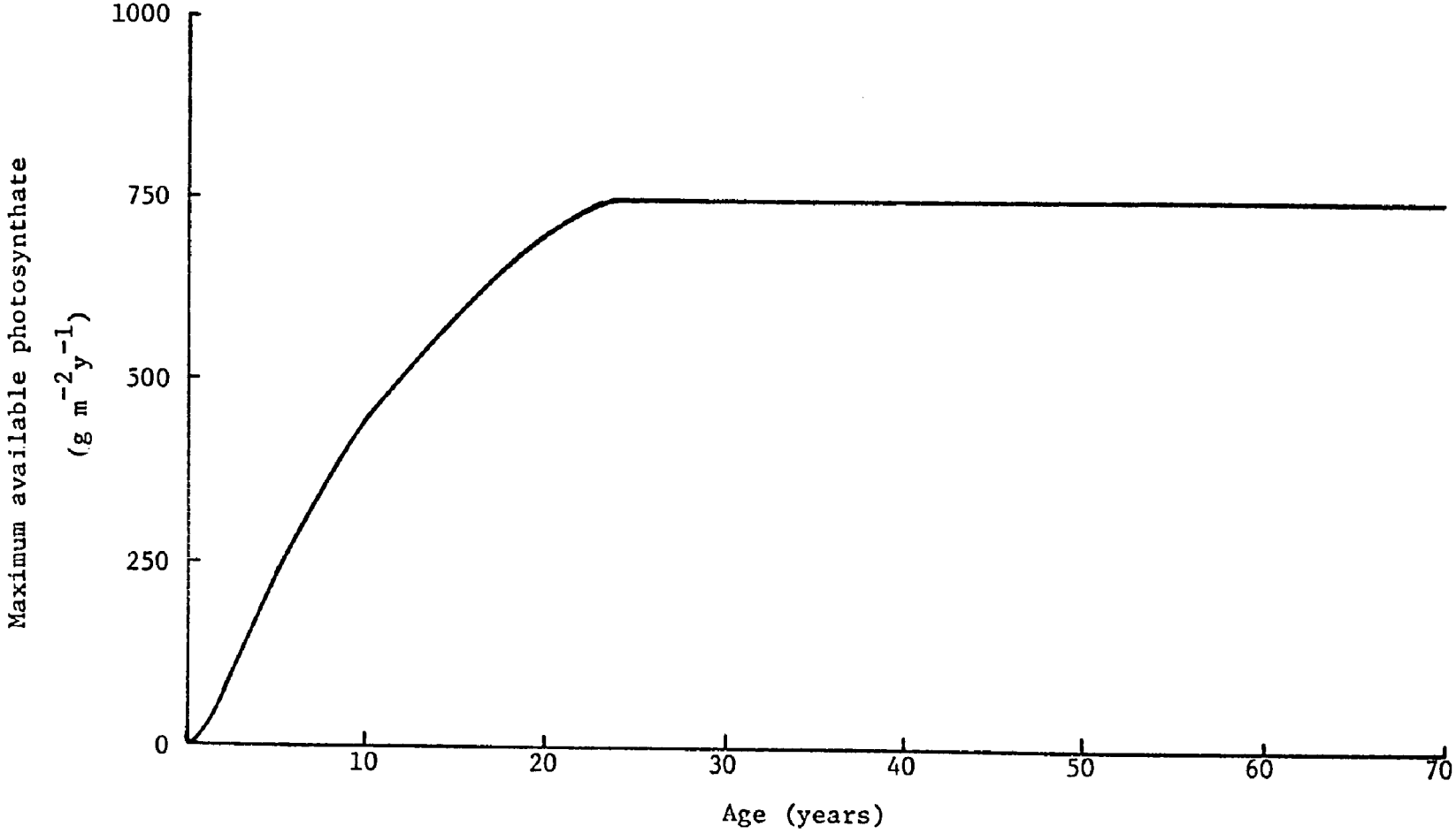
Discussion: In more sophisticated versions of this model this flow would result from photosynthesis which is affected by various

environmental factors. In this version photosynthate is produced from table values as discussed in detail in SUBROUTINE CYCL1.

I define photosynthate in this paper as that amount of photosynthetic material that is made available by the leaves for redistribution to all growing organs. The curve used for estimation of the magnitude of photosynthate production was taken from Rodin and Bazelivich (1967, Fig. 8). The actual values used in this model were taken from a curve pictured in Fig. 4. The curve represents the amounts of photosynthate assumed to be produced in a lodgepole pine forest with the dimensions of stand 1-1 under conditions of growth which are not limited by low concentrations of potassium. The curve does not represent gross primary production (Odum 1971) in that total plant respiration is unknown. The curve represents net primary productivity (Odum 1971) plus respiration factors for stems and trunks.

The important underlying assumptions state that after the initial stages of growth, 10 to 15 years, the proportions of photosynthate distributed to the various organs of the trees become constant (Tables FRGFT, FBGFT, FTGFT, FCGFT, and FNGFT in Appendix D, parameter values). A list of coefficient names, definitions and their units is given in Appendix F. The photosynthate produced increases with age for the first 25 years and thereafter remains constant in non-nutrient limited systems. As biomass of the trees increases, largely due to the increase of trunks, respiration also increases (Odum 1971) and net primary production decreases (Rodin and Bazelivich 1967, Fig. 8).

Figure 4. Maximum available photosynthate as a function of stand age assuming no nutrient limitations.


Maximum available photosynthate
(g m^{-2}y^{-1})
1000
750
500
250
0
10
20
30
40
50
60
70
Age (years)

All three systems evaluated show some degree of nutrient limitation with photosynthate production as a function of age and available nutrients while photosynthate distribution is governed by relative total plant biomass.

The amount of photosynthate produced under ideal conditions at a given time step is multiplied by a function in SUBROUTINE CYCL1, which describes the relative yield of biomass as a function of available K in the soil nutrient pool (X_{27}). This function was developed from information in Black (1968, p. 729). The assumption is made that the amount of K is X_{27} at year 70 under fire-maintained conditions is the least amount that will produce about 90 to 95% maximal yield of biomass (Fig. 4). As X_{27} increases the increase in yield is minimal. But, as X_{27} decreases, yield decreases exponentially.

To summarize, photosynthate (TEMP), which is a function of forest age and nutrient availability, is distributed upon demand which is a function of total plant biomass, to the first year needles (X_1), cones (X_5), twigs (X_6), trunks (X_7), and roots (X_8) in the amounts TEMPN, TEMPC, TEMPT, TEMPB, and TEMPR, respectively.

(98, 1).

FLOW DEFINITION: Flow of photosynthate to growing tissues of needles.

SIMCOMP code: (98, 1). F = TEMPN

Discussion: The flow of photosynthate (TEMP) to the first-year needles was estimated from curves in Rodin and Bazelivich (1967) which were adjusted to meet the dimensions of the lodgepole pine stand (Moir and Francis 1972). The first-year needle biomass

should increase until about year 25 when the steady-state is achieved for needles (leaf abscission from X_3 and X_4 equals production in X_1). The decimal values that represent the demand for photosynthate by needles (TEMPN) are read from the array FNGFT. This array and others, representing tables, are discussed in SUBROUTINE CYCL1 and FUNCTION TABLE (A, B, C, D, E).

(1, 2).

FLOW DEFINITION: Flow of first-year needles to second-year needles.

SIMCOMP code: (1, 2). F = X(1)/DT

Discussion: This flow is assumed to be the total amount of first-year needles (X_1). X_1 is divided by DT (time interval in this case 1) to have F in the proper units and to compute the proper flow independent of time.

(1, 9), (2, 9), (3, 9), (4, 9),
(5, 9), (6, 9), (7, 9).

FLOW DEFINITION: Flow of above-ground organic matter out of the system via harvest or fire.

SIMCOMP code: none

Discussion: These values are perturbation dependent. The flows are chosen by the investigator and implemented in the initial conditions and by updating the system in SUBROUTINE CYCL1. The values for the flows are presented in Appendix E and explained in Model Output (pp. 77-79).

(1, 10)., (2, 10).

FLOW DEFINITION: Flow of first and second-year needles to litter.

SIMCOMP code: none

Discussion: The transfer of first (X_1) and second (X_2) year needles to the litter (X_{10}) is assumed to be dependent upon the harvest practice employed and the amount of slash left on the site. During years of undisturbed growth the value is zero. Implementation of the flows are handled as discussed in (1, 9) etc.

(2, 3).

FLOW DEFINITION: Flow of second-year to third-year (X_3) needles.

SIMCOMP code: (2, 3) F = X(2)/DT

Discussion: This flow is similar to (1, 2).

(3, 4).

FLOW DEFINITION: Flow of third-year to fourth-year (X_4) needles.

SIMCOMP code: (3, 4) F = .575* X(3)/DT

Discussion: This is the portion of needles that remain viable and carry over to the fourth year. The flow is assumed to be a constant times X_3.

(3, 10).

FLOW DEFINITION: Flow of third-year needles to litter.

SIMCOMP code: (3, 10). F = .425* X(3)/DT

Discussion: This rate is the portion of third-year needles that abcise and fall to the forest floor as litter during a year of normal growth. Total needlefall is described in Moir (1972). I assume this value to be a constant times X_3. This rate can be altered by harvest as discussed in (1, 10) and (2, 10).

(4, 10).

FLOW DEFINITION: The flow of fourth-year needles to litter.

SIMCOMP code: (4, 10). F = X(4)/DT

Discussion: The total amount of X_4 falls as litter. Actual longevity of needles is sometimes longer but for the purposes of this model four years is assumed to be average.

(98, 5).

FLOW DEFINITION: Flow of photosynthate to produce new cones.

SIMCOMP code: (98, 5). F = TEMPC

Discussion: After 10 years this flow looks similar to that for needles (98, 1). The proportion of photosynthate channeled to cones (TEMPC) is a fraction of the perennial above-ground parts of Rodin and Bazelivich (1967) and Moir (1972). Through the first 10 years, the rate is zero since lodgepole pine generally produce no cones in the early stages of development (Fowells 1965). The production of cones is very erratic varying widely from year to year. However, considering the long-term resolution of this model, I feel the use of average values is appropriate.

In this version of the model the proportion of material that flows to the cones is controlled by values read into the program from the FCGFT array discussed in SUBROUTINE CYCL1 and FUNCTION TABLE (A, B, C, D, E).

(5, 10).

FLOW DEFINITION: Flow of cones (X_5) to litter.

SIMCOMP code: (5, 10). F = X(5)* CLIP (0., CLR, 25., AGE)

TEMP5 = F

Discussion: This flow is controlled by a CLIP function subroutine which states that if the age (AGE) of the stand is less than 25 years the flow will be zero. If the age is greater than or equal to 25 years the rate is CLR or 0.09 times cone biomass (X_5)

(Moir 1972). The 25-year value was selected as the approximate age at which the canopy is fully developed and the lower branches begin to die and self-pruning commences. Fall of cones parallels branch fall because of the close adherence of the cones to the branches (Clements 1910). CLR is greater than TLR, the loss coefficient for twigs discussed below, because of selective pruning by squirrels. TEMP5 as well as TEMP6, TEMP7, TEMP8, and TEMP10 below are book-keeping variables used in calculating concentrations of potassium in cones, twigs, trunks, roots, and litter, respectively.

(98, 6).

FLOW DEFINITION: Flow of photosynthate to twigs.

SIMCOMP code: (98, 6). F = TEMPT

Discussion: Photosynthate accumulated in the branches, X_6, (living and dead) is a fraction of the perennial above-ground parts (Rodin and Bazelivich 1967 and Moir 1972). The rate of increase of twigs is assumed to nearly parallel the increase of needles through the first 25 or 30 years. Values are called from array FTGFT.

(6, 10).

FLOW DEFINITION: Flow of twigs to litter.

SIMCOMP code: (6, 10). F = X(6)* CLIP (0., TLR, 25., AGE)

TEMP6 = F.

Discussion: As discussed in (5, 10). this flow starts at about age 25 and is assumed to proceed at a rate TLR times X_6 thereafter (Moir 1972). The calculation is made by a clip function as in (5, 10). Since the rate is small it is not changed in the various perturbation simulations, however, a correction could be easily made by adjusting the value to be a percentage of stem biomass.

(6, 99).

FLOW DEFINITION: Flow of twig organic matter to the atmosphere as CO_2 via respiration.

SIMCOMP code: (6, 99). F = .01 * X(6).

Discussion: This flow is calculated as a constant times the total stem biomass (X_6). The value was adjusted to the proper magnitude to produce the desired results rather than being based on data since none were available.

(98, 7).

FLOW DEFINITION: Flow of photosynthate to trunks.

SIMCOMP code: (98, 7). F = TEMPB

Discussion: The values for flow of photosynthate to the trunks (X_7) (from Function Table FBGFT) is similar to that for needles except for magnitude. The amount is the remainder of the amount distributed to perennial above-ground biomass illustrated in Rodin and Bazelivich (1967) and Moir (1972).

(7, 10).

FLOW DEFINITION: Flow of trunk material to litter.

SIMCOMP code: (7, 10). F = X(7)* CLIP (0., SLR, 25., AGE)

TEMP7 = F.

Discussion: In the mature system trunk material (mostly bark) is assumed to be lost at a rate SLR which is a fraction of X_7. The flow occur from year 25 on. The calculation is made with a CLIP function as in (5, 10).

(7, 99).

FLOW DEFINITION: Flow of trunk material to the atmosphere via respiration.

SIMCOMP code: (7, 99). F = 0.19* X(7).

Discussion: This calculation is similar to that for (6, 99) except that it is based on the total biomass of the trunks and thus has a different coefficient.

(98, 8).

FLOW DEFINITION: Flow of photosynthate to roots.

SIMCOMP code: (98, 8). F = TEMPR

Discussion: This calculation is similar to those for needles and trunks. The rate of flow of photosynthate to the roots (X_8) is governed by the portion allocated from curves found in Rodin and Bazelivich (1967) and adjusted to the proper magnitude with data of Moir (1972). The underlying assumption is that roots contain 25% of the plant biomass at maturity.

(8, 11)., (8, 12).

FLOW DEFINITION: Collective flow of organic matter from roots to mineral soil via death and respiration.

SIMCOMP code: (8, 11). F = .25* X(8)* RLR

TEMP8 = F/.25

(8, 12). F = .75* X(8)* RLR

Discussion: Data regarding turnover rates of roots (X_8) are inadequate or wholly unavailable (Kozlowski 1971). Therefore, both root death and organic matter losses via respiration are lumped into the same calculations and numerous estimates must be made. RLR is the root loss rate.

I estimate 25% of the living roots occur in the A1 horizon and 75% in the combined A2-B2 horizons of the mineral soils. In the calculation these percentages are multiplied by the supposed root

loss rate (RLR) due to respiration and death. To determine RLR, coefficients were adjusted to achieve steady-state conditions at 70 years.

Following fire or clearcutting I assume several years are required for the soil microbes to decompose the newly acquired soil organic matter (McFee and Stone 1966).

(10, 11).

FLOW DEFINITION: Flow of organic matter from litter (X_{10}) to the A1 soil horizon (X_{11}).

SIMCOMP code: (10, 11). F = RLA1* X(10)

TEMP 10 = F.

Discussion: This flow is calculated from an adjusted constant (RLA1) times the total of litter organic matter.

(10, 99).

FLOW DEFINITION: Flow of litter organic matter to the atmosphere via microbial respiration.

SIMCOMP code: (10, 99). F = CLIP

(X(10) + X(4) + .425* X(3)/DT,.1*

X(10)/DT, 25., AGE)

Discussion: The amount of material that accumulates in the litter horizon is a function of all inputs mentioned previously and losses via (10, 11). and respiration. Here the assumption is made that losses via (10, 11). are small compared to respiration. Thus (10, 99). is the only flow in the main program that must be changed according to treatment. The other flows all remain the same.

In the fire-maintained system a CLIP function calculates that all litter material that falls to the ground for 25 years is

respired away. The 25-year value is based on the observations of Trimble and Tripp (1949) who suggest that about 25 years are required for a well developed litter mat to begin development after fire or clearcutting. This time span coincides with the approximate time required for canopy closure in a developing forest. After 25 years the litter layer develops rather rapidly and reaches steady-state. In the code for clearcut treatments the litter left at the soil surface is respired away at accelerated rates by microbes. After 25 years both systems behave identically.

(10, 13)., (11, 13).

FLOW DEFINITION: Loss of carbon via erosion.

SIMCOMP code: (11, 13). F = ERODO

Discussion: The values for erosion are read into the program as the TABLE function FEOFT. These values were estimated using the Universal Erosion Equation of Wischmeier and Smith (1965). Losses probably occur for 6 or 7 years (Orr 1970) until enough vegetation has regenerated to cause effective erosion control. In the fire-maintained system most surface organic matter is assumed to be consumed during the fire and only small losses occur via erosion. The other perturbations cause differential erosion losses depending on the quantity of slash left on the forest floor. In this model all loss is from (11, 13). and none is from (10, 13). since data is unavailable regarding the relative amounts lost from either soil horizon.

(11, 12).

FLOW DEFINITION: Flow of carbon from the A1 horizon (X_{11}) to the A2-B2 horizons (X_{12}) via translocation.

SIMCOMP code: (11, 12). F = RA1A2* X(11).

Discussion: This rate is probably very small when compared to the input from roots. The rate is a decimal fraction of X_{11}.

(11, 99)., (12, 99).

FLOW DEFINITION: Flow of organic matter from the mineral soils to the atmosphere via respiration.

SIMCOMP CODE: (11, 99). F = CLIP

(.06* X(11), .2* X(11), 720., X(11)

(12, 99). F = CLIP

(.06* X(12), .2* X(12), 185 ., X(12)

Discussion: These are functions that must account for the respiration of increased organic matter following perturbation and ultimately the stabilization of soil organic matter (X_{11} and X_{12}) as the forest matures. These functions are in the form of coefficients multiplied by the amount of carbon in the appropriate compartment and were obtained by manipulation.

(27, 14)., (14, 15).,

(15, 16)., (16, 17).

FLOW DEFINITION: Flow of K to the first-year needles and through the needle age classes.

SIMCOMP code: (27, 14). F = FKIN * TEMPN

(14, 15). F = X(14)/DT

(15, 16). F = X(15)/DT

(16, 17). F = X(16)/DT

Discussion: X_{27} is a dummy compartment used to sum the soil nutrient pool ($X_{24} + X_{25}$) and is the basis of the nutrient response calculation mentioned earlier. These flows are the amounts of K in the

needles (FKIN) expressed as percentage of biomass in TEMPN, X_1, X_2, and X_3, respectively. The reader is reminded that I have made the assumption that the K concentration remains constant for each living organ. Values for FKIN as well as other constants of K concentration are given in Appendix D. FKIN is based on unpublished data of Dr. W. H. Moir.

(27, 18)., (27, 19)., (27, 20)., (27, 21).

FLOW DEFINITION: Flows of potassium from the soil reserves to the cones, twigs, trunks and roots, respectively.

SIMCOMP code: (27, 18). F = FKICT * TEMPC
(27, 19). F = FKICT * TEMPT
(27, 20). F = FKIB * TEMPB
(27, 21). F = FKIR * TEMPR

Discussion: These flows are directly proportional to their biomass counterparts. That is, the concentrations of potassium in the cones (FKICT) times TEMPC, twigs (FKICT) times TEMPT, trunks (FKIB) times TEMPB and roots (FKIR) times TEMPR yield the appropriate flows of K to the remaining live tissues. The concentrations of K in twigs and cones and that in trunks and roots are assumed to be equal. These concentrations were taken from Rodin and Bazelivich (1967, Table 16).

(14, 22)., (15, 22)., (16, 22)., (17, 22)., (18, 22)., (19, 22)., (20, 22).

FLOW DEFINITION: Flow of K out of the system via harvest.

SIMCOMP code: None

Discussion: Since K is directly proportional to organic matter this discussion parallels that for the flows of biomass out of the system via harvest.

(14, 23)., (15, 23)., (16, 23).,
(17, 23)., (18, 23)., (19, 23).,
(20, 23).

FLOW DEFINITION: The flow of K to litter.

SIMCOMP code: (16, 23). F = .425* X(16)/DT
(17, 23). F = X(17)/DT
(18, 23). F = FKICT * TEMP5
(19, 23). F = FKICT * TEMP6 + .01* .0026* X(6)
(20, 23). F = FKIB * TEMP7 + .019* .0006* X(7)

Discussion: The code refers to the normal rates of litter fall. Harvest manipulations are set in the program through initial conditions and SUBROUTINE CYCL1. These flows are proportional to their biomass counterparts and depend on the state of growth or harvest practice utilized. The harvest practice dictates the amount of slash left as litter.

(14, 24)., (15, 24)., (16, 24).,
(17, 24)., (18, 24)., (19, 24).,
(20, 24).

FLOW DEFINITION: The flow of K to the A1 horizon as a result of fire.

SIMCOMP code: None

Discussion: These are the amounts of K contained in the various above-ground compartments that are deposited on the soil as ash in the event of fire. These values are set in initial conditions and SUBROUTINE CYCL1.

(21, 24)., (21, 25).

FLOW DEFINITION: Flow of K to soil via dying roots.

SIMCOMP code: (21, 24). F = FKIR * TEMP8 * .25

(21, 25). F = FKIR * TEMP8 * .75

Discussion: These flows are the amounts of K released by dying roots. Real values for these functions are unknown. The proportions of roots roots in the two horizons are described above.

(23, 24).

FLOW DEFINITION: Flow of K from litter to A1 horizon.

SIMCOMP code: (23, 24). F = CLIP (.95* (X(17) + .425 *
X(16) + .95* .0023 * X(10)/DT, .4 *
X(23), 25., AGE)

Discussion: When plant material is released from the living system as litter the assumption of constant concentrations of K becomes invalid. The movement of nutrients in the litter and soil systems becomes a function of leaching and soil properties such as cation exchange capacity and microbial immobilization. It is conceivable that 95% of the K may be leached out of newly fallen needle material and into the lower horizons in the first year (Nykvist 1959 and Curlin 1970). As a result of fire all nutrients are assumed to be released to the A1 horizon. As forest regrowth proceeds nearly all litter is consumed by oxidative processes and all K is released to the A1 horizon. This process occurs until the canopy closes sufficiently to allow litter accumulation as suggested in (10, 11). when litter begins to accumulate at 25 years. The assumption is made that nutrients begin to accumulate at a concentration of .0023 times X_{10} (FKIL). This value is calculated from Moir and Grier (1969)

and is probably valid when the litter mat has developed all of its subhorizons. The concentrations of K in the litter in the period between the commencement of litter buildup and development of all subhorizons is unknown.

A CLIP function is used to insure that, following clearcutting, litter and K will be removed at accelerated rates as decomposition and leaching occur. During the first 25 years 95% of the K in any litter material will be leached into the A1 horizon. Thereafter, 40% is lost to the A1.

(24, 26).

FLOW DEFINITION: Flow of K from the A1 horizon to the A2-B2 horizons.

SIMCOMP code: (24, 25). F = LEACH

Discussion: The A1 horizon is assumed to be the zone of most active cycling of nutrients. However, reliable data on the dynamics of nutrients in soils in semi-arid forests is non-existant. For the purposes of this model the following cycle of events is assumed. Following perturbation, nutrients are released from ash, slash, and litter and are transferred to the A1 horizon. Here for the first few years after treatment the K is trapped by 1) residual colloids in the A1 horizon and newly developed colloids introduced by dead roots resulting in increased C.E.C.; and 2) immobilization by microbial species whose populations explode following the introduction of fresh substrate. Doubtless some of these nutrients are lost via erosion and leaching but these amounts are regarded as small when compared to the amount retained. Within two or three years annual and temporary perennial plants develop (Clements 1910) on the site and absorb nutrients resulting in retention of the elements near

the surface of the soil. As the young forest develops and in the presence of abundant nutrients near the soil surface, the young trees exhibit luxury consumption of elements thus completing the cycle of nutrient retention.

For purposes of this model, nutrients are assumed to be depleted from the A1 horizon first as a result of the events just described and then are drawn from the lower horizon. The 1.9 g m^{-2} amount is assumed to be the minimum to which K can be reduced in the compartment.

To define the flow explicitly, I assume that the increased amount of material leached out of the A2-B2 horizon (X_{25}) is replaced by a like amount leached in from the A1 horizon (X_{24}).

(24, 27)., (25, 27).

FLOW DEFINITION: Summation of the soil nutrient pool.

SIMCOMP code: None

Discussion: This flow is used to calculate the soil nutrient pool. It does not represent a real flow of K. The value of the pool is calculated in SUBROUTINE START and SUBROUTINE CYCL1. The appropriate amounts of K in X_{24} and X_{25} at each time step are calculated in SUBROUTINE CYCL2.

(23, 26)., (24, 26).

FLOW DEFINITION: Loss of K as a result of erosion.

SIMCOMP code: (24, 26). F = ERODE

Discussion: Since the relative dimensions of these flows after perturbation are unknown the losses from the system via erosion are assumed as losses from the A1 horizon (X_{24}) and none from the litter horizon (X_{23}). The assumptions state that following perturbation

erosion losses increase drastically, for some treatments, up to about 6 or 7 years when vegetational cover again is sufficient to reduce erosion losses to near zero. Estimates of the magnitude of erosion losses are made using the Universal Erosion Equation of Wischmeier and Smith (1965), and data of Orr (1970), Leaf (1966), and Stottlemyer and Ralston (1970) give data which can be used for comparisons.

The estimates for these losses (ERODE) are calculated from the array FEFT via a TABLE function in SUBROUTINE CYCL1.

(25, 29).

FLOW DEFINITION: Flow of K out of system via leaching losses from the A2-B2 horizons.

SIMCOMP code: (25, 29). F = LEACH

Discussion: Estimates of losses of K from the system are calculated from the array FLFT via the TABLE function (LEACH). These estimates were made using the data of Stottlemyer and Ralston (1970) and Likens et al. (1970). Their data represent the concentrations of nutrient in the effluent from watersheds. I arrived at my values by estimating a probable amount of water that would be available to be moved through the entire profile under the present climatic regime in the lodgepole pine forest. This amount was corrected for total amount of precipitation that might be expected (20-22 inches per year), the amount expected as rain (about one-half of total precipitation), the amount of rain or snow intercepted by foliage, the amount needed to recharge the soil system each spring, and etc. Between 3 and 5 inches of water were calculated to percolate through the profile.

The amount (about 4 inches) is multiplied by concentrations of K in stream water found by the above authors giving an estimate of leaching losses. In this version of the model the values shown in the tables FLFT were all truncated due to a programming error. However, the truncated value are as reasonable as the values shown in the tables (30, 24).

FLOW DEFINITION: Flow of K into the system from the atmosphere.

SIMCOMP code: (30, 24). F = 0.05

Discussion: This is a constant taken from Junge and Werby (1958). (28, 25).

FLOW DEFINITION: Flow of K into the system from the weathering of soil parent material.

SIMCOMP code: (28, 25). F = .093

Discussion: Less is known about the amount of nutrients made available to the living system via weathering than any of the other input or output factors. Two lines of reasoning were used to arrive at a value for this rate and fortunately both agree rather closely.

Using the line of reasoning followed by Johnson et al. (1968) for the weathering of rock minerals in the Hubbard Brook Study in New Hampshire, a value for the weathering rate of K was calculated for a type of rock similar to that under the pine stand (Tyrrell 1926). The value chosen would apply to the Hubbard Brook area and according to Curry (1970) should be divided by 2 to estimate the weathering rate of rock in the semi-arid mountains of the west. The value arrived at through this line of reasoning is about 0.11 $g\ m^{-2}\ year^{-1}$.

The other more subjective reasoning followed suggests that if Equation 2 (above) holds, then over a fire-growth cycle of 70 years inputs equal outputs or:

$$\Sigma(Wi + Pi) = \Sigma(NE_o + NL_o) + \Sigma(AE_o + AL_o)$$

where all components are defined in Equations 1 and 2. Rearranging Equation 2 gives:

$$Wi = NE_o + NL_o + AE_o + AL_o - Pi$$

Summing over 70 years:

$$\sum_{i=1}^{70} Wi = \sum_{i=1}^{70}(NE_o + NL_o + AE_o + AL_o - Pi)$$

and

$$\sum_{i=1}^{70} Wi/70 = \text{annual input K via weathering.}$$

The estimate obtained depends upon the assumption that values for erosion, leaching, and inputs from the atmosphere are know. Estimates of these values are not precise, but using this line of reasoning with my best estimate gives a value of 0.093 g m^{-2} $year^{-1}$ of K as a weathering rate.

This discussion ignores a potential input of K via an equilibrium established between non-exchangeable K and exchangeable K (Black 1968, pp. 665-676). Some research has shown that certain

micaceous soil minerals establish equilibria while others do not. Since nothing is known about the mineralogical properties of these lodgepole pine soils the contribution of non-exchangeable K to the nutrient capital is assumed to be negligible.

Subroutines

The lodgepole pine model contains several subroutines which do many of the calculations needed in the description of the flows above. Some of these subroutines only simplify input and output processes, others do simple bookkeeping calculations and yet other portions of the subroutines do calculations have important biological implications. Only the latter of these functions will be discussed in detail. A complete listing of the subroutines is given in Appendix D.

Subroutine Start

All of the calculations of SUBROUTINE START are of a bookkeeping nature. The first block of code (See Appendix D) calculates the various concentrations of nutrients in the system. The last calculation simply sums the potassium pool in the soil horizons. One should see Gustafson and Innis (1972) for a description of the calls to the subroutines.

Subroutine CYCL1

SUBROUTINE CYCL1, again refer to Gustafson and Innis (1972), is called at the beginning of each computational cycle. It is called prior to the calculation of the flows. Therefore, one can lump into CYCL1 a number of calculations which need to be repeated from one flow to the next.

The first block of code from line 76 to line 89 places the appropriate amounts of organic matter and potassium into the appropriate compartments following the first perturbation at 70 years. The next block of code line 90 to line 101 repeats the first block except beginning at year 140.

Lines 102, 103, and 104 compute the appropriate table values for erosion and leaching of K and erosion of organic matter.

The next five lines of code are bookkeeping in nature. The next three lines of code calculate the amount of photosynthate that will be available for redistribution. The calculation of FK represents a curve whose shape is seen in Fig. 3. This calculation is written in FORTRAN language and represents $FK = 1 - e^{-.68\ X_{27}}$.

The biological implications of this function and the following were discussed in (99, 98). of the previous section. GFA (AGE) is called from the FUNCTION SUBROUTINE GFA (Y) and represents the maximum potential photosynthate available for growth assuming no nutrient limitations. TEMP (line 113) is the product of GFA (AGE) and FK and represents the actual amount of photosynthate available for forest growth.

The next block of code, line 114 to line 118, calls the FUNCTION subroutine TABLE (A, B, C, D, E) which presents the relative amounts of photosynthate, as decimal fractions, that can be distributed to needles, cones, twigs, trunks, and roots, respectively. In essence, the functions state that as total plant biomass (TPB) increases, photosynthate increases to a level above which it remains constant. In this version of the model constant proportions of material are reached before the 16800 g m^{-2}, level of biomass is reached as shown

in the call statements. The last block of code normalizes the demand by the various components of living biomass against the total demand to provide a decimal fraction between zero and one for each component. This operation insures the total of the values are 1.0.

Subroutine CYCL2

This subroutine represents a bookkeeping function for the soil nutrient pool. It calculates the amount of potassium that has been withdrawn from the A1 and A2-B2 horizons. The subroutine also sums the needle biomass.

Model Output

This section contains the output from the lodgepole pine model described above. The graphical outputs show the exercise of the model as a result of the variation of some of the parameters and allows one to gain some feel for the potential of this kind of modeling effort. Printed outputs give the numerical values of the state variables at years 0, 70, 140, and 210. All values are given in g m^{-2}.

The 12 graphs show in sets of 4, the results of three model runs. Each run simulated three forest perturbation - regrowth cycles. The first graph in each set shows the dynamics of needle, cone, twig, trunk and root organic matter. The second graph shows litter organic matter and carbon from the A1 and A2-B2 horizons. The third graph shows the K dynamics of the forest floor and the two horizons of mineral soil. The fourth graph in each set shows total plant biomass and total content of K in the systems.

The potassium contents of the plant material is not shown here because, as discussed in previous sections, the nutrient is directly proportional to the biomass of a given plant organ. The proportionality constants are 0.0103, 0.0026, 0.0026, 0.0006, and 0.0010 for needles, cones, twigs, trunks, and roots, respectively.

The scales for a number of these graphs are different so that the information is shown to full scale. While this has some advantages it is sometimes misleading when one attempts a visual comparison of one curve with another.

One of the fundamental objectives of the exercise was to simulate the biomass and nutrient dynamics of a system assumed to be burned at average intervals of 70 years. In this treatment, all above-ground components including litter, are consumed by fire and the K contained therein deposited on the A1 horizon of the soil (Appendix E). The roots become soil organic matter and their K is released to the mineral soil. Erosion occurs for seven years and accelerated leaching for six years after fire.

The shapes of the curves produced by the simulation are reasonable except, possibly for the magnitude of the oscillations in the A1 horizon organic matter compartment (Figs. 5, 6, 7 and 8). The magnitude of the A2-B2 horizon should be multiplied by 10. However, reliable data on the dynamics of soil carbon are unavailable to confirm or deny the observation. The total amount of K in the systems builds up by an amount of about 1.1 g m^{-2} in the 210 year run but this buildup is considered well within acceptable limits for this model.

This run represents the pulse-stable system described in detail in the first section of this part. The printed output (Simulation Output 1) gives the actual values of the simulation at years 0, 70, 140 and 210, indicating that all values at the end of each cycle were near the 70-year estimated values for the forest (Fig. 2).

A clearcutting practice was simulated in which boles were removed from the system and the slash (needles, cones, and twigs) were left at the site as litter to be decomposed at accelerated rates (Appendix E). Nutrients are released to the Al horizon. Roots behave as in the fire-maintained system. Erosion occurs but at reduced rates when compared to the fire-maintained system due to soil stabilization caused by the slash. Leaching occurs at accelerated rates similar to the fire-maintained system for six years because of K release from the slash and dead roots.

The curves appear to be reasonable except as discussed in the fire-maintained system (Figs. 9, 10, 11, and 12). Nutrient limitation begins to take effect and each successive clearcut cycle yields smaller amounts of biomass in the individual organs (compartments) and a consequent smaller total plant biomass (TPB). At the end of the 210-year cycle the system supports about 2000 g m^{-2} less than the fire-maintained system and has lost 15 to 20% of its K capital (Simulation Output 2).

The third exer ise of the model simulated 70 year harvest cycles. The boles were removed from the system at harvest and the slash was assumed to have been raked out of the cutting area and burned (Appendix E). Erosion occurs at the same high values as the fire-maintained system but leaching does not increase because all

above-ground sources of nutrients were removed. The response of the system (Figs. 13, 14, 15, and 16) was similar to that of the previous treatment except that it was more extreme with biomass reduced by 3000 g m^{-2} and 42% of the K lost from the system when compared to the fire-maintained system (Simulation Output 3).

The second version of this model is now being developed in which the concentration of K in the tissues varies directly with the amount of exchangeable K in the soil and the amount of photosynthate available for growth is a function of the concentration of K in the needles. Preliminary outputs are similar to those produced in version one.

Conclusion

This model is the first version or skeleton of what hopefully will become an expanded, more precise simulation model. The model is sufficiently general to allow easy adjustment to address other questions raised about similar ecosystems. The model can also be easily adjusted to address similar questions about more complex systems. Further development depends on more adequate data, time, and resources.

This version has demonstrated that a mathematical model can be developed that can rather realistically represent the dynamics of biomass and at least one nutrient in a lodgepole pine forest. Further, the model has shown that, based on available data and the assumptions stated previously, certain clearcutting practices can result in drastically reduced nutrient pools and consequent reduction of production of tree biomass.

The model was built around only one cation, K, because one of the objectives was to develop a system of equations that would

yield plausible simultations of growth and nutrient dynamics. As stated in a previous section, data on K is more reliable than for any other element we examined. As a result, a simple model was built that had a sound base of data rather than a complex model that had a less reliable data base.

Nutrient inputs into the system via weathering and precipitation, and outputs via erosion and leaching are factors that require a great deal more study before models of high precision can be developed.

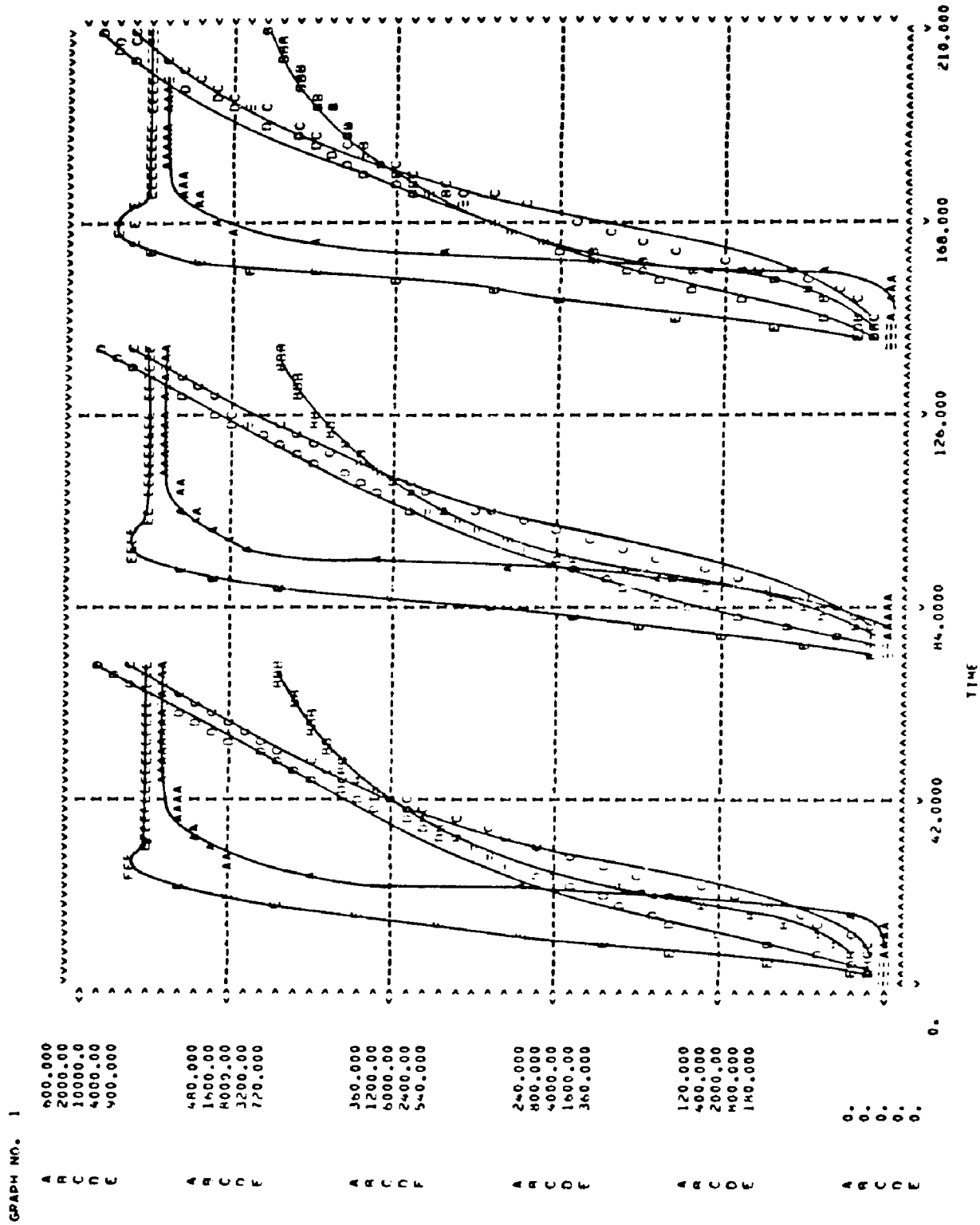
Specific information must be obtained about the response of lodgepole pine trees to increased or decreased nutrients. The nutrient response curve in Fig. 3 is probably the correct form but the actual status of the current forest soils, upon which the assumptions are based, is unknown. The estimates used in developing the nutrient response function were intuitively based.

Unfortunately, a whole realm of biological endeavor, physiological effects of insufficient nutrients (K), was neglected in this version of the model. For example, flower and seed production are only two of the important physiological processes linked to K availability. Reliable quantitative information about K control of these processes in lodgepole pine trees is not available.

Research should be conducted to determine if the bulk of the exchangeable potassium located in the A2-B2 horizons of this system, or others like it, is truly available. My observations and those of W. H. Moir indicate most tree roots are located in upper 20 cm of the soil profile and very few small roots terminate in the lower portion of the B horizons. These observations strongly suggest

that even though exchangeable K occurs in relatively large quantities in the lower horizons much of it may indeed be unavailable. If this conclusion is valid then as a result of clearcutting, far more drastic decreases in production of plant biomass are to be expected than this model indicated.

Figure 5. SIMCOMP simulation of organic matter (g m^{-2} oven dry weight) dynamics of trees in a fire-maintained lodgepole pine stand. The stand is assumed to have burned three times at 70 year intervals. A = X(5) = cones; B = X(6) = twigs; C = X(7) = boles; D = X(8) = roots; E = X(1) + X(2) + X(3) + X(4) = TOTN = Needles.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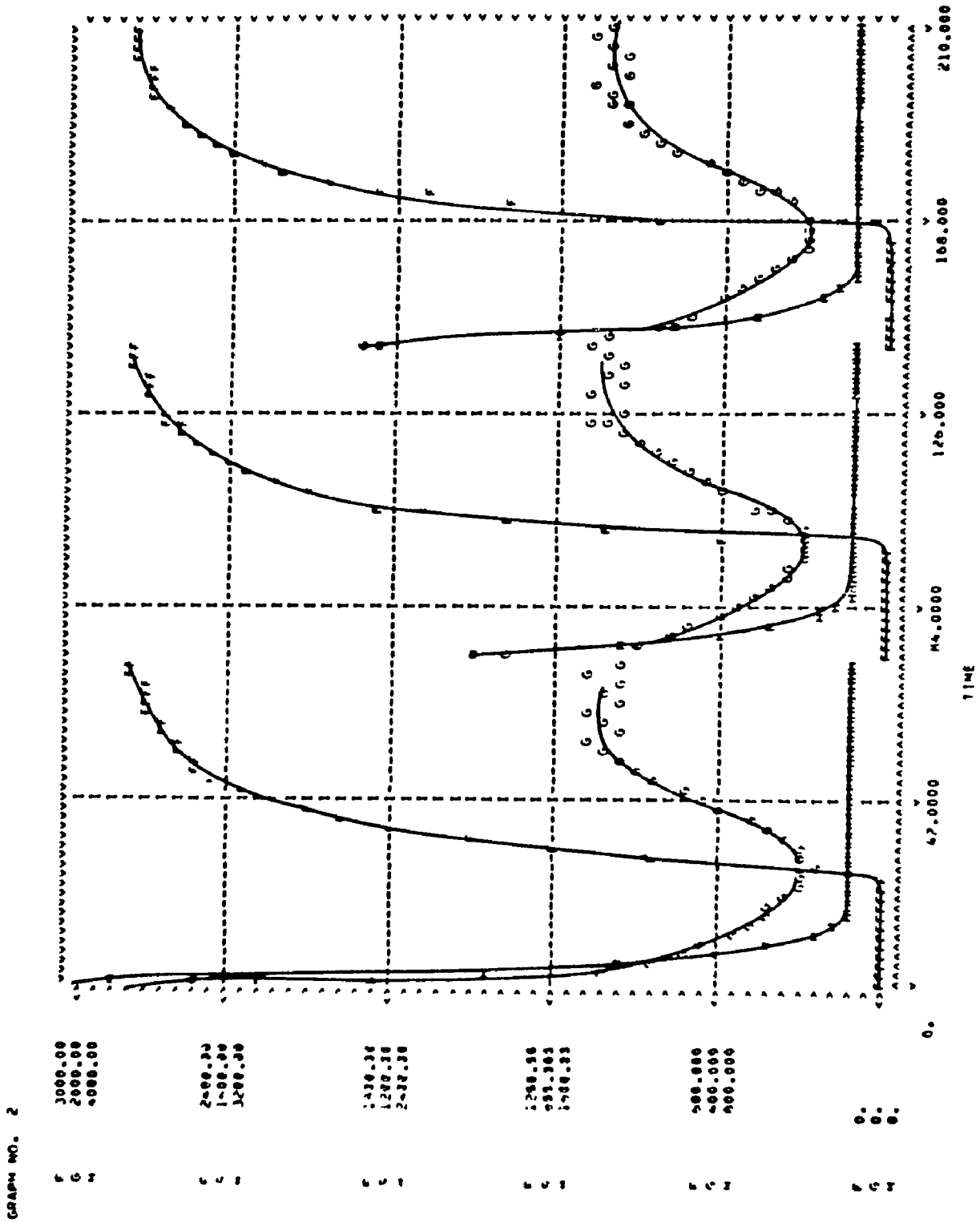
B 2000.00
C 10000.0
D 4000.00
E 900.000
A 480.000
B 1600.00
C 8000.00
D 3200.00
E 720.000
A 360.000
B 1200.00
C 6000.00
D 2400.00
E 540.000
A 240.000
B 800.000
C 4000.00
D 1600.00
E 360.000
A 120.000
B 400.000
C 2000.00
D 800.000
E 180.000
A 0.
B 0.
C 0.
D 0.
E 0.
0.
42.0000
84.0000
126.000
168.000
210.000
TIME

Figure 6. SIMCOMP simulation of organic matter (g m^{-2} oven dry weight) dynamics of the forest floor and mineral soils in a fire-maintained lodgepole pine stand. The stand is assumed to have burned three times at 70 year intervals. F = X(10) = forest floor material; G = X(11) = A1 horizon; H = X(12) = combined A2-B2 horizons.


GRAPH NO. 2
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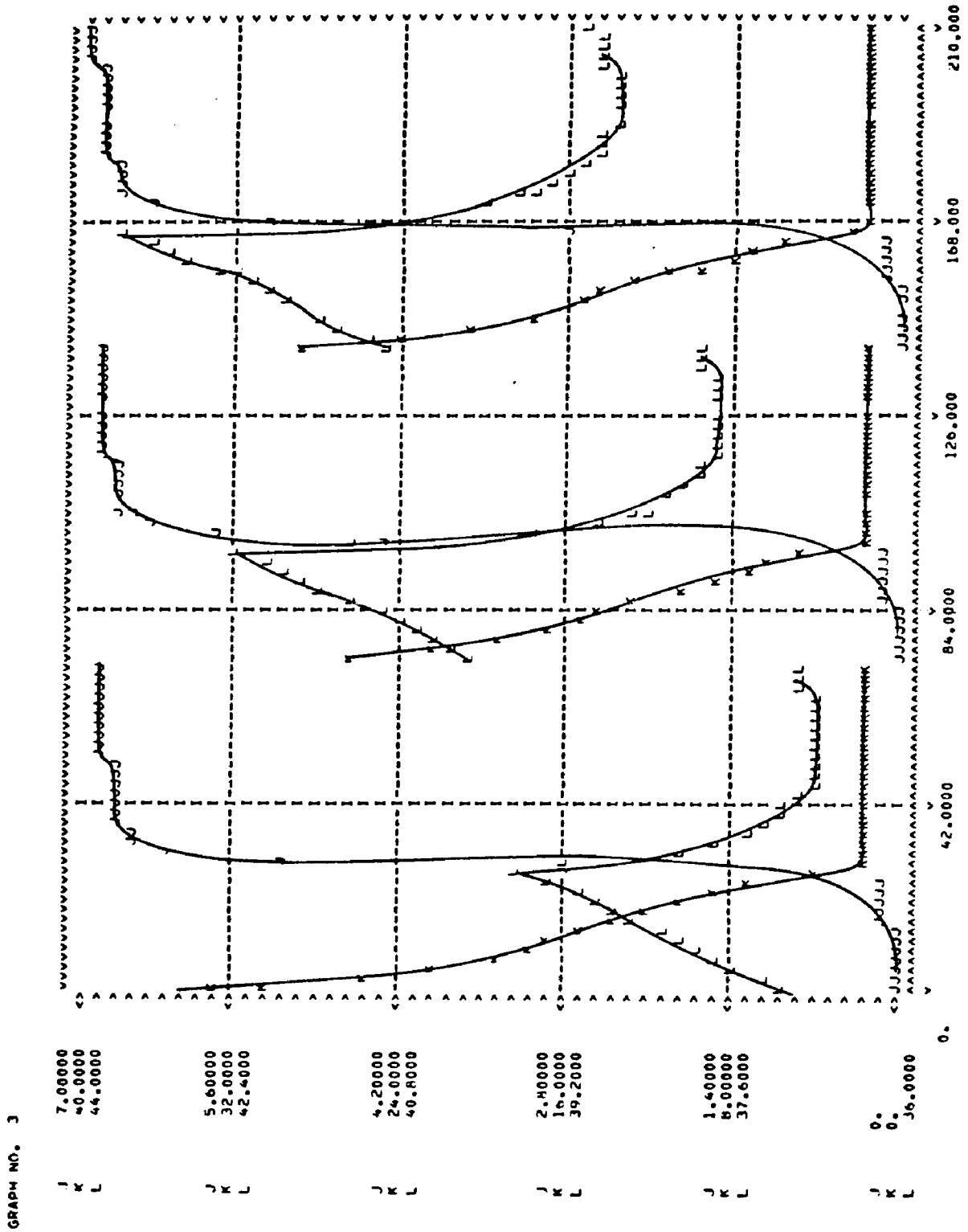
1000.00
0.
42.0000
84.0000
126.000
168.000
210.000
TIME

Figure 7. SIMCOMP simulation of K (g m^{-2} oven dry weight) dynamics of the forest floor and mineral soils in a fire-maintained lodgepole pine stand. The stand is assumed to have burned three times at 70 year intervals. J = X(23) = forest floor; K = X(24) = A1 horizon; L = X(25) = combined A2-B2 horizons.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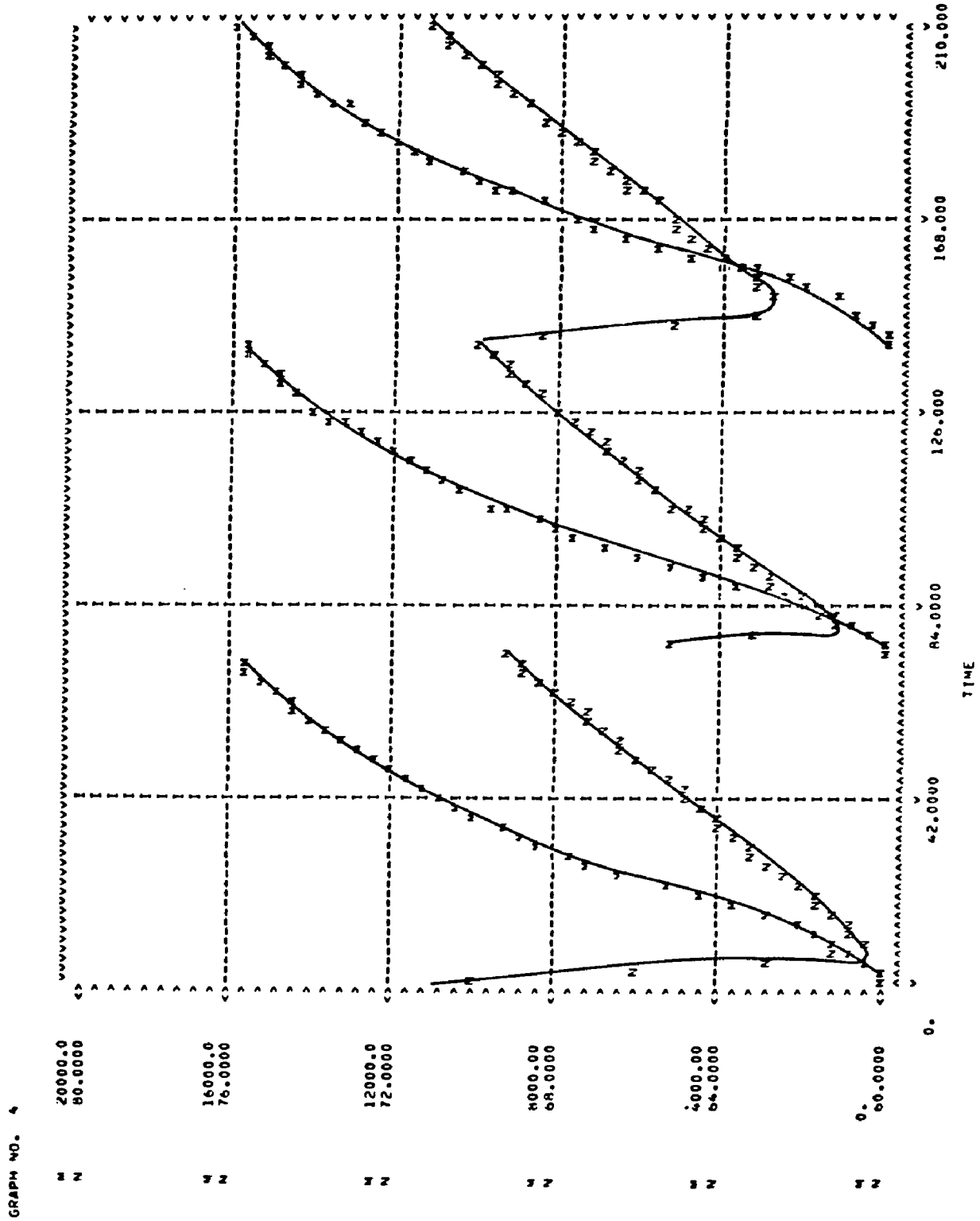
L 44.0000
J 5.60000
K 32.0000
L 42.4000
J 4.20000
K 24.0000
L 40.8000
J 2.80000
K 16.0000
L 39.2000
J 1.40000
K 8.00000
L 37.6000
J 0.
K 0.
L 36.0000
0.
42.0000
84.0000
126.000
168.000
210.000
TIME

Figure 8. SIMCOMP simulation of total plant biomass (M=TPB) and total K in the system (N=TOTK) in a fire-maintained lodgepole pine stand. The stand is assumed to have burned three times at 70 year intervals. M and N are both in g m^{-2} (oven dry weight).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76.0000
12000.0
72.0000
8000.00
68.0000
4000.00
64.0000
0.
60.0000
0.
42.0000
84.0000
126.000
168.000
210.000
TIME

Simulation Output 1. Numerical output for the simulation of forest growth and K cycling in a fire-maintained lodgepole pine forest (time is in years and values are in g m^{-2}).

SIMULATION OUTPUT

TIME = 0.

X(1)	=	1.00000000	X(2)	=	0	X(3)	=	0	X(4)	=	0
X(5)	=	0	X(6)	=	0	X(7)	=	0	X(8)	=	0
X(10)	=	0	X(11)	=	1720.00000	X(12)	=	3875.00000	X(13)	=	0
X(14)	=	.103000000E-01	X(15)	=	0	X(16)	=	0	X(17)	=	0
X(18)	=	0	X(19)	=	0	X(20)	=	0	X(21)	=	0
X(23)	=	0	X(24)	=	33.1000000	X(25)	=	37.1000000	X(26)	=	0
X(27)	=	70.2000000	X(28)	=	1000.00000	X(29)	=	1000.00000	X(30)	=	1000.00000
X(98)	=	0	X(99)	=	1000.00000	TPB	=	0	TEMP	=	0
TOTK	=	70.2103000	TOTN	=	0						

TIME = 70.0000000

X(1)	=	229.943898	X(2)	=	229.903549	X(3)	=	229.865418	X(4)	=	132.152010
X(5)	=	540.733259	X(6)	=	1518.23284	X(7)	=	9392.90690	X(8)	=	3923.67533
X(10)	=	2401.24441	X(11)	=	652.814543	X(12)	=	184.043712	X(13)	=	292.060000
X(14)	=	2.36942215	X(15)	=	2.36800956	X(16)	=	2.36761380	X(17)	=	1.36116570
X(18)	=	1.40590647	X(19)	=	3.94740538	X(20)	=	5.63574414	X(21)	=	3.92367533
X(23)	=	6.89482862	X(24)	=	1.90000000	X(25)	=	37.0475319	X(26)	=	1.000000000
X(27)	=	36.0097262	X(28)	=	993.490000	X(29)	=	1010.00000	X(30)	=	996.500000
X(98)	=	.727595761E-11	X(99)	=	28916.2302	TPB	=	16071.8870	TEMP	=	696.799690
TOTK	=	69.0773000	TOTN	=	821.864875						

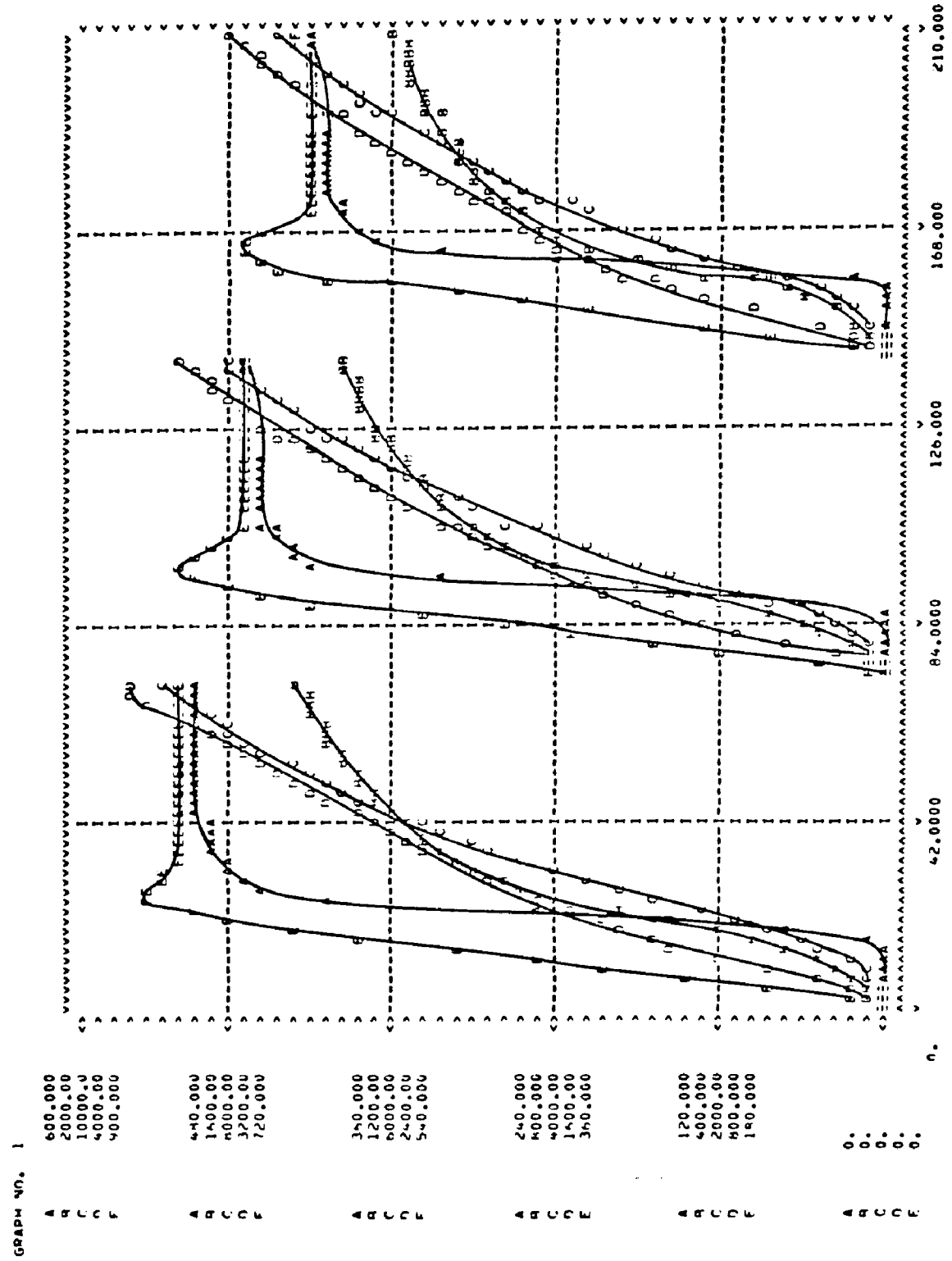
TIME = 140.000000

X(1)	=	231.112352	X(2)	=	231.072240	X(3)	=	231.040234	X(4)	=	132.829259
X(5)	=	543.512886	X(6)	=	1525.58812	X(7)	=	9438.02277	X(8)	=	3939.41222
X(10)	=	2415.48925	X(11)	=	656.052014	X(12)	=	184.757878	X(13)	=	484.120000
X(14)	=	2.38045722	X(15)	=	2.38007497	X(16)	=	2.37971441	X(17)	=	1.36814137
X(18)	=	1.41313350	X(19)	=	3.96652910	X(20)	=	5.66281366	X(21)	=	3.93941222
X(23)	=	6.93010769	X(24)	=	1.90000000	X(25)	=	38.0599158	X(26)	=	1.85000000
X(27)	=	37.0078375	X(28)	=	986.980000	X(29)	=	1318.00000	X(30)	=	993.000000
X(98)	=	.393797881E-11	X(99)	=	55588.4564	TPB	=	16146.3309	TEMP	=	700.340460
TOTK	=	70.2374000	TOTN	=	826.057086						

TIME = 210.000000

X(1)	=	232.212201	X(2)	=	232.172075	X(3)	=	232.145946	X(4)	=	133.466632
X(5)	=	546.125000	X(6)	=	1532.44706	X(7)	=	9480.38285	X(8)	=	3954.22923
X(10)	=	2424.47106	X(11)	=	679.243679	X(12)	=	192.275911	X(13)	=	676.180000
X(14)	=	2.39178567	X(15)	=	2.39143418	X(16)	=	2.39110324	X(17)	=	1.37470631
X(18)	=	1.41992500	X(19)	=	3.98446636	X(20)	=	5.68822471	X(21)	=	3.95422923
X(23)	=	6.96329260	X(24)	=	1.90000000	X(25)	=	39.0911277	X(26)	=	2.70000000
X(27)	=	38.0155355	X(28)	=	980.470000	X(29)	=	1026.00000	X(30)	=	984.500000
X(98)	=	.727595761E-11	X(99)	=	82638.0092	TPB	=	16216.2681	TEMP	=	703.673337
TOTK	=	71.3973000	TOTN	=	830.002855						

Figure 9. SIMCOMP simulation of organic matter (g m^{-2} oven dry weight) dynamics of trees in a lodgepole pine stand subjected to clearcutting (slash left in place) three times at 70 year intervals. A = X(5) = cones; B = X(6) = twigs; C = X(7) = boles; D = X(8) = roots; E = X(1) + X(2) + X(3) + X(4) = TOTN = needles.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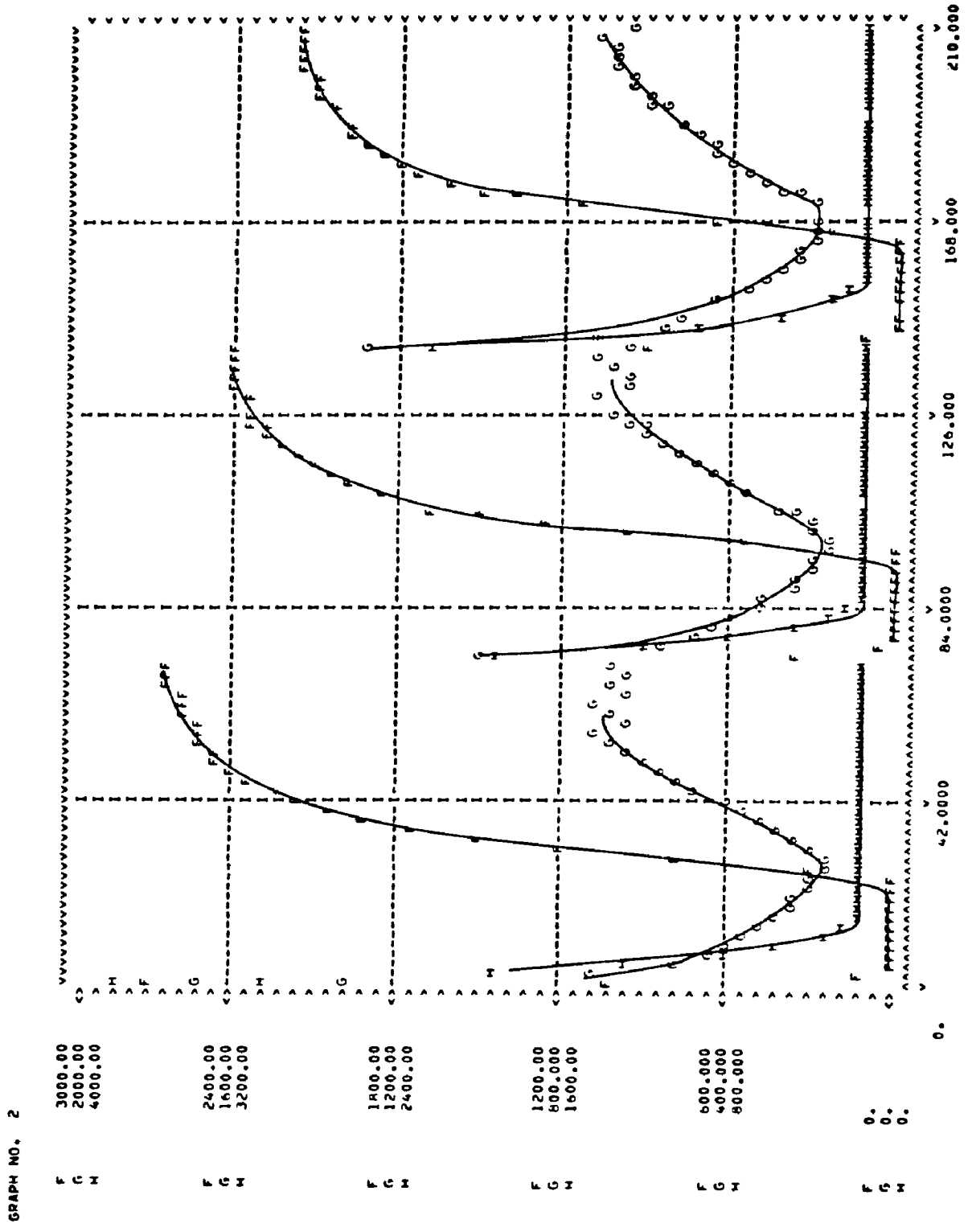
B 2000.00
C 10000.0
D 4000.00
E 400.000
A 440.000
B 1400.00
C 6000.00
D 3200.00
E 720.000
A 340.000
B 1200.00
C 6000.00
D 2400.00
E 540.000
A 240.000
B 800.000
C 4000.00
D 1600.00
E 360.000
A 120.000
B 400.000
C 2000.00
D 800.000
E 180.000
A 0.
B 0.
C 0.
D 0.
E 0.
0.
42.0000
84.0000
126.000
168.000
210.000
TIME

Figure 10. SIMCOMP simulation of organic matter (g m^{-2} oven dry weight) dynamics of the forest floor and mineral soils in a lodgepole pine stand subjected to clear-cutting (slash left in place) three times at 70 year intervals. F = X(10) = forest floor; G = X(11) = A1 horizon; H = X(12) = combined A2-B2 horizons.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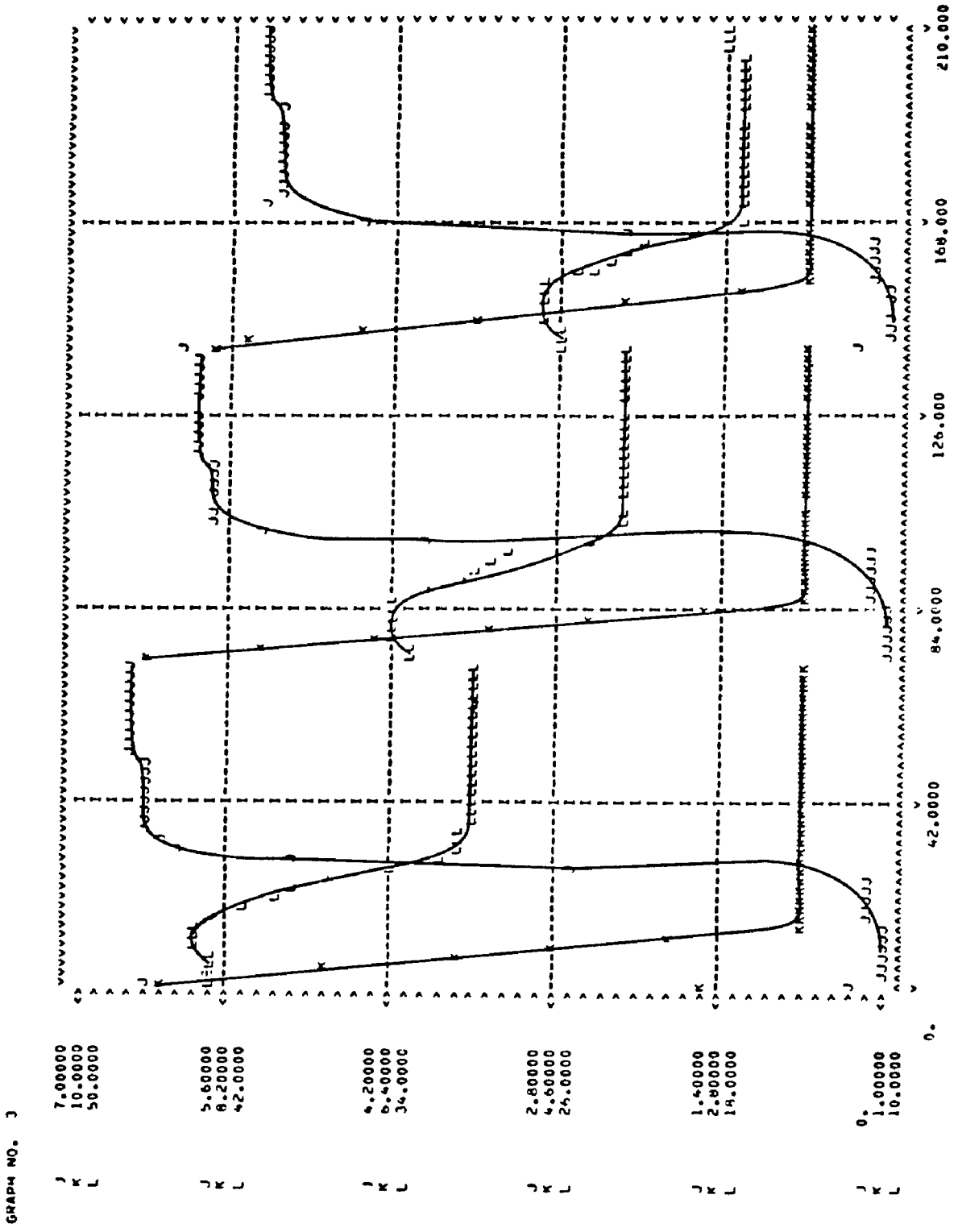
G 2000.00
H 4000.00
F 2400.00
G 1600.00
H 3200.00
F 1800.00
G 1200.00
H 2400.00
F 1200.00
G 800.000
H 1600.00
F 600.000
G 400.000
H 800.000
F 0.
G 0.
H 0.
0.
42.0000
84.0000
126.000
168.000
210.000
TIME

Figure 11. SIMCOMP simulation of K (g m^{-2} oven dry weight) dynamics of the forest floor and mineral soils in a lodgepole pine stand subjected to clearcutting (slash left in place) three times at 70 year intervals. J = X(23) = forest floor; K = X(24) = A1 horizon; L = X(25) = A2-B2 horizons.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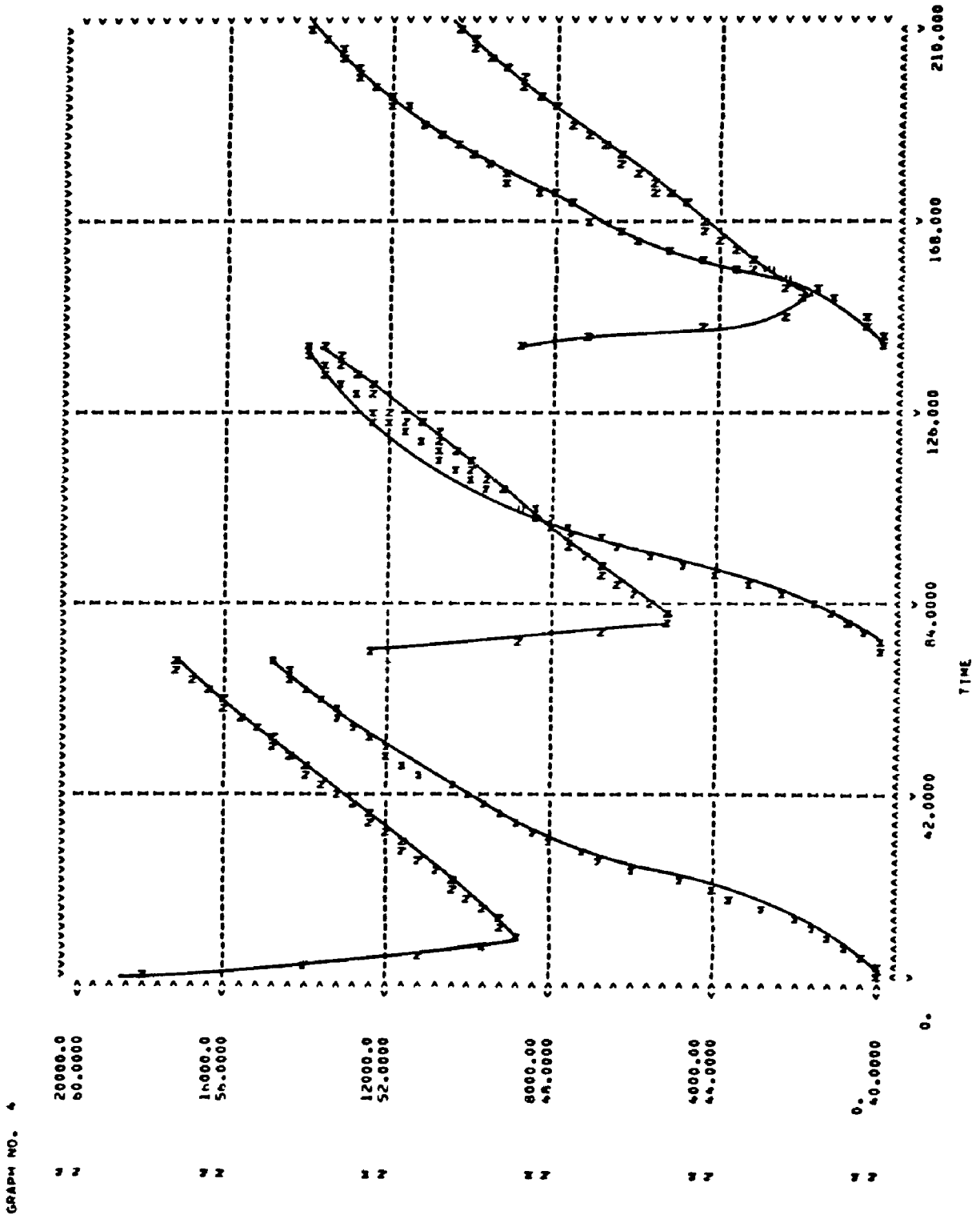
K 10.0000
L 50.0000
J 5.60000
K 8.20000
L 42.0000
J 4.20000
K 6.40000
L 34.0000
J 2.80000
K 4.60000
L 26.0000
J 1.40000
K 2.80000
L 18.0000
J 0.
K 1.00000
L 10.0000
0.
42.0000
84.0000
126.000
168.000
210.000
TIME

Figure 12. SIMCOMP simulation of total plant biomass (M=TPB) and total K in the system (N=TOTK) in a lodgepole pine stand subjected to clearcutting (slash left in place) three times at 70 year intervals. M and N are both in g m^{-2} (oven dry weight).


GRAPH NO. 4
20000.0
60.0000
16000.0
56.0000
12000.0
52.0000
8000.00
48.0000
4000.00
44.0000
0.
40.0000
0.
42.0000
84.0000
126.000
168.000
210.000
TIME

Simulation Output 2. Numerical output for the simulation of forest growth and K cycling in a lodgepole pine forest subjected to clearcutting with slash left in place (time is in years and values are in g m^{-2}).

SIMULATION OUTPUT

TIME = 0.

X(1)	=	1.00000000	X(2)	=	0	X(3)	=	0	X(4)	=	0
X(5)	=	0	X(6)	=	0	X(7)	=	0	X(8)	=	0
X(10)	=	5217.60000	X(11)	=	1720.00000	X(12)	=	3875.00000	X(13)	=	0
X(14)	=	.103000000E-01	X(15)	=	0	X(16)	=	0	X(17)	=	0
X(18)	=	0	X(19)	=	0	X(20)	=	0	X(21)	=	0
X(23)	=	12.0004800	X(24)	=	3.10000000	X(25)	=	43.2000000	X(26)	=	0
X(27)	=	46.3000000	X(28)	=	1000.00000	X(29)	=	1000.00000	X(30)	=	1000.00000
X(98)	=	0	X(99)	=	1000.00000	TPH	=	0	TEMP	=	0
TOTK	=	58.3107800	TOTN	=	0						

TIME = 70.0000000

X(1)	=	214.304858	X(2)	=	214.215833	X(3)	=	214.130112	X(4)	=	123.077498
X(5)	=	503.255889	X(6)	=	1417.97597	X(7)	=	8775.28239	X(8)	=	3707.62972
X(10)	=	2608.47547	X(11)	=	644.125620	X(12)	=	199.546195	X(13)	=	292.060000
X(14)	=	2.20734004	X(15)	=	2.20642308	X(16)	=	2.20554016	X(17)	=	1.26769823
X(18)	=	1.30446531	X(19)	=	3.68673752	X(20)	=	5.26516944	X(21)	=	3.70762972
X(23)	=	6.42064909	X(24)	=	1.90000000	X(25)	=	27.6851274	X(26)	=	.460000000
X(27)	=	26.8304442	X(28)	=	993.490000	X(29)	=	1010.00000	X(30)	=	996.500000
X(98)	=	.363797881E-11	X(99)	=	32562.5904	TPH	=	15053.7252	TEMP	=	649.408661
TOTK	=	57.7177800	TOTN	=	765.728101						

TIME = 140.000000

X(1)	=	207.452567	X(2)	=	207.339805	X(3)	=	207.230617	X(4)	=	119.096956
X(5)	=	486.704959	X(6)	=	1373.10335	X(7)	=	8496.61019	X(8)	=	3609.49682
X(10)	=	2522.94394	X(11)	=	707.501803	X(12)	=	178.388120	X(13)	=	484.120000
X(14)	=	2.13678144	X(15)	=	2.13580000	X(16)	=	2.13447535	X(17)	=	1.22669865
X(18)	=	1.26543289	X(19)	=	3.57006870	X(20)	=	5.09796611	X(21)	=	3.60943682
X(23)	=	6.21167871	X(24)	=	1.90000000	X(25)	=	24.9272319	X(26)	=	.850000000
X(27)	=	24.1661974	X(28)	=	986.980000	X(29)	=	1018.00000	X(30)	=	993.000000
X(98)	=	.363797881E-11	X(99)	=	62482.4854	TPH	=	14594.7292	TEMP	=	628.644144
TOTK	=	54.0726104	TOTN	=	741.119946						

TIME = 210.000000

X(1)	=	200.006520	X(2)	=	199.866823	X(3)	=	199.730873	X(4)	=	114.769321
X(5)	=	468.645867	X(6)	=	1323.74570	X(7)	=	8188.76853	X(8)	=	3500.49922
X(10)	=	2427.37154	X(11)	=	650.453922	X(12)	=	182.596720	X(13)	=	676.180000
X(14)	=	2.06006716	X(15)	=	2.05862828	X(16)	=	2.05722799	X(17)	=	1.18212401
X(18)	=	1.21847926	X(19)	=	3.44173881	X(20)	=	4.91326112	X(21)	=	3.50049922
X(23)	=	5.99444341	X(24)	=	1.90000000	X(25)	=	22.4211748	X(26)	=	1.24000000
X(27)	=	21.7524127	X(28)	=	980.470000	X(29)	=	1026.00000	X(30)	=	989.500000
X(98)	=	.363797881E-11	X(99)	=	91598.2467	TPH	=	14087.7329	TEMP	=	606.080364
TOTK	=	50.5946445	TOTN	=	714.373537						

Figure 13. SIMCOMP simulation of organic matter (g m^{-2} oven dry weight) dynamics of trees in a lodgepole pine stand subjected to clearcutting (slash removed) three times at 70 year intervals. A = X(5) = cones; B = X(6) = twigs; C = X(7) = boles; D = X(8) = roots; E = X(1) + X(2) + X(3) + X(4) = TOTN = Needles.

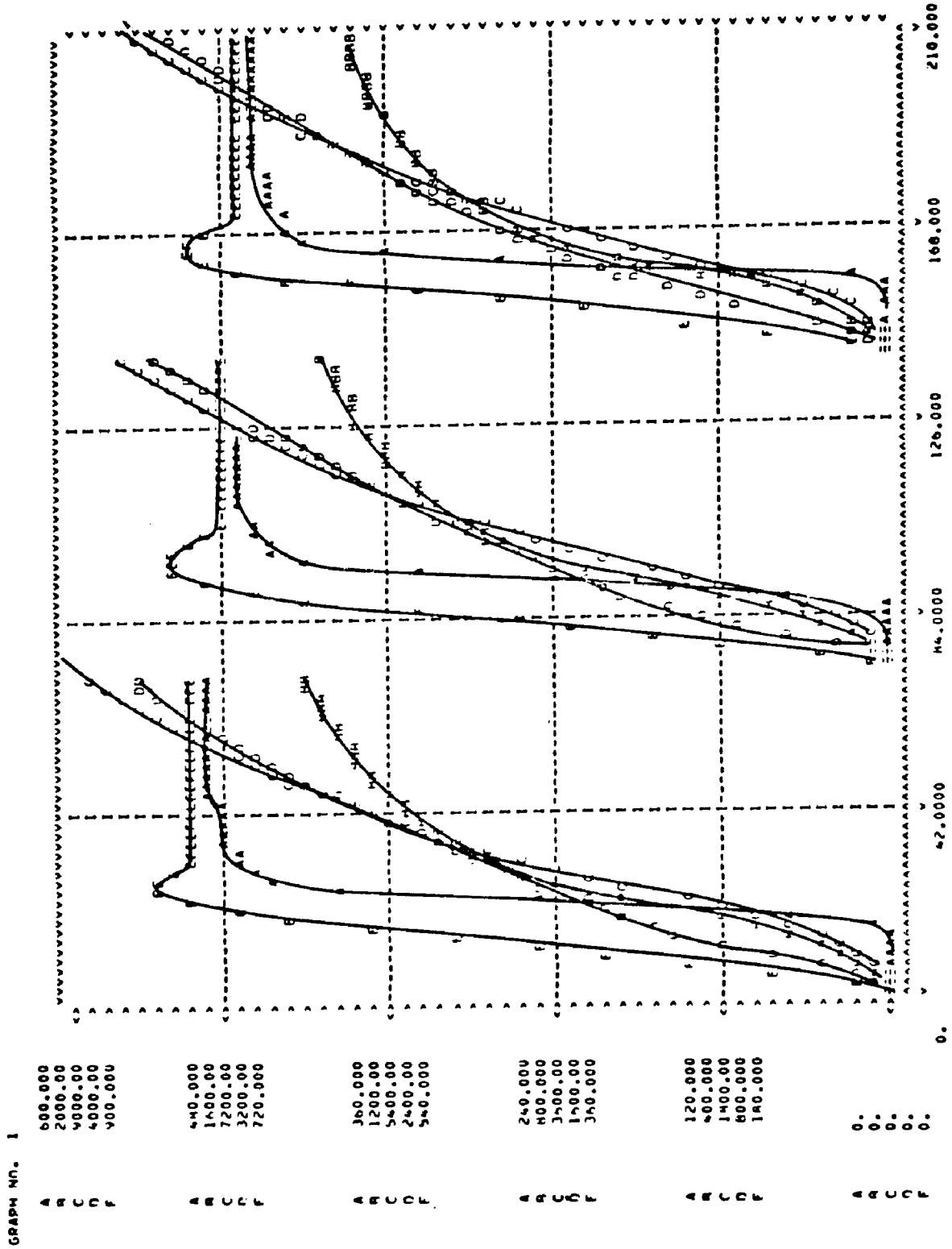

GRAPH NO. 1
A 800.000
B 2000.00
C 4000.00
D 4000.00
F 400.000
A 440.000
B 1400.00
C 7200.00
D 3200.00
F 720.000
A 360.000
B 1200.00
C 5400.00
D 2400.00
F 540.000
A 240.000
B 800.000
C 3600.00
D 1600.00
F 360.000
A 120.000
B 400.000
C 1400.00
D 800.000
F 180.000
A 0.
B 0.
C 0.
D 0.
F 0.
0.
42.0000
84.0000
126.000
168.000
210.000
TIME

Figure 14. SIMCOMP simulation of organic matter (g m^{-2} oven dry weight) dynamics of the forest floor and mineral soils in a lodgepole pine stand subjected to clearcutting (slash removed) three times at 70 year intervals. F = X(10) = forest floor; G = X(11) A1 horizon; H = X(12) = combined A2-B2 horizons.

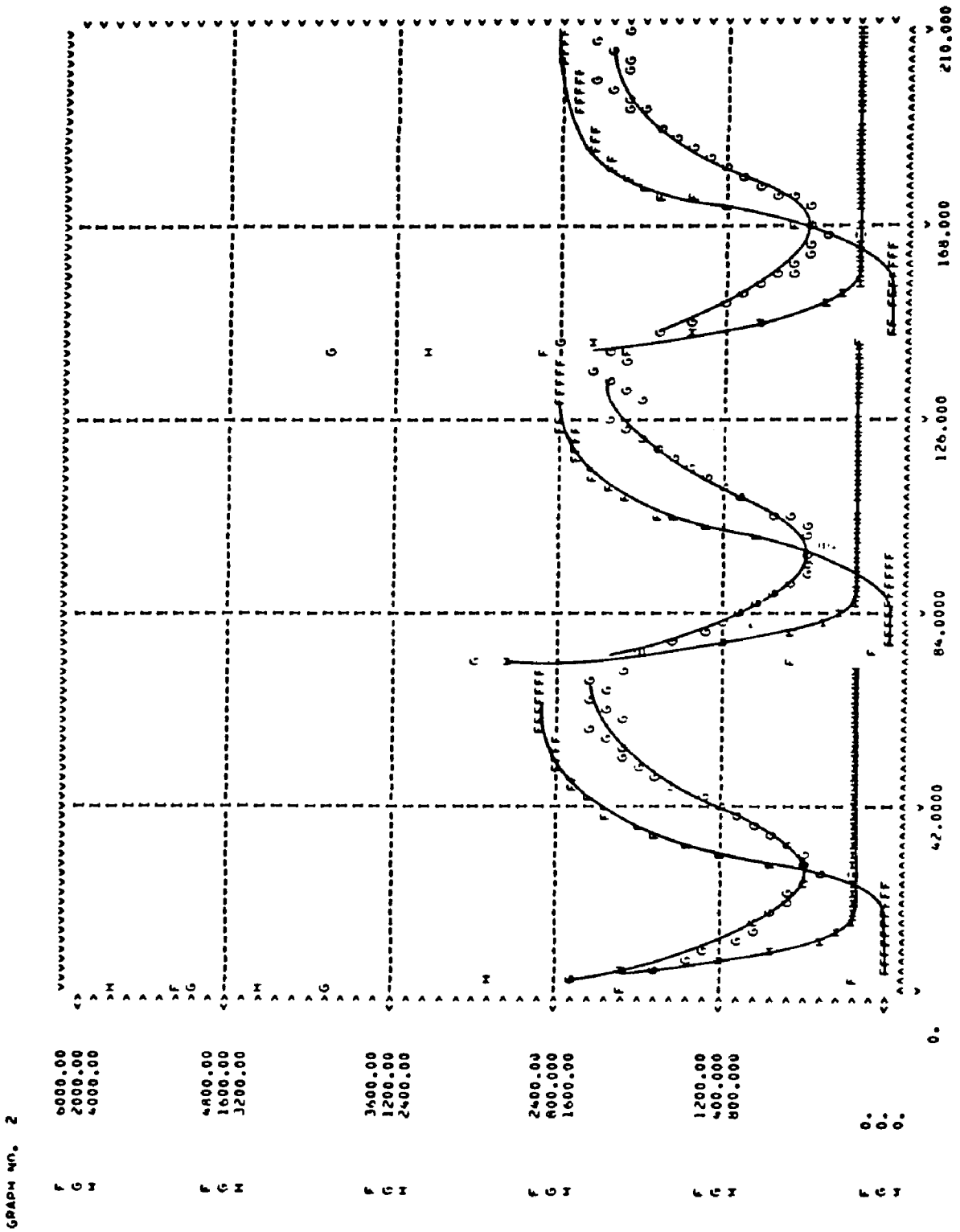

GRAPH NO. 2
F
G
M
6000.00
2000.00
4000.00
4800.00
1600.00
3200.00
3600.00
1200.00
2400.00
2400.00
800.000
1600.00
1200.00
400.000
800.000
0.
0.
0.
0.
42.0000
84.0000
126.000
168.000
210.000
TIME

Figure 15. SIMCOMP simulation of K (g m^{-2} oven dry weight) dynamics of forest floor and mineral soils in a lodgepole pine stand subjected to clearcutting (slash removed) three times at 70 year intervals. J = X(23) = forest floor; K = X(24) = A1 horizon; L = X(25) = combined A2-B2 horizons.

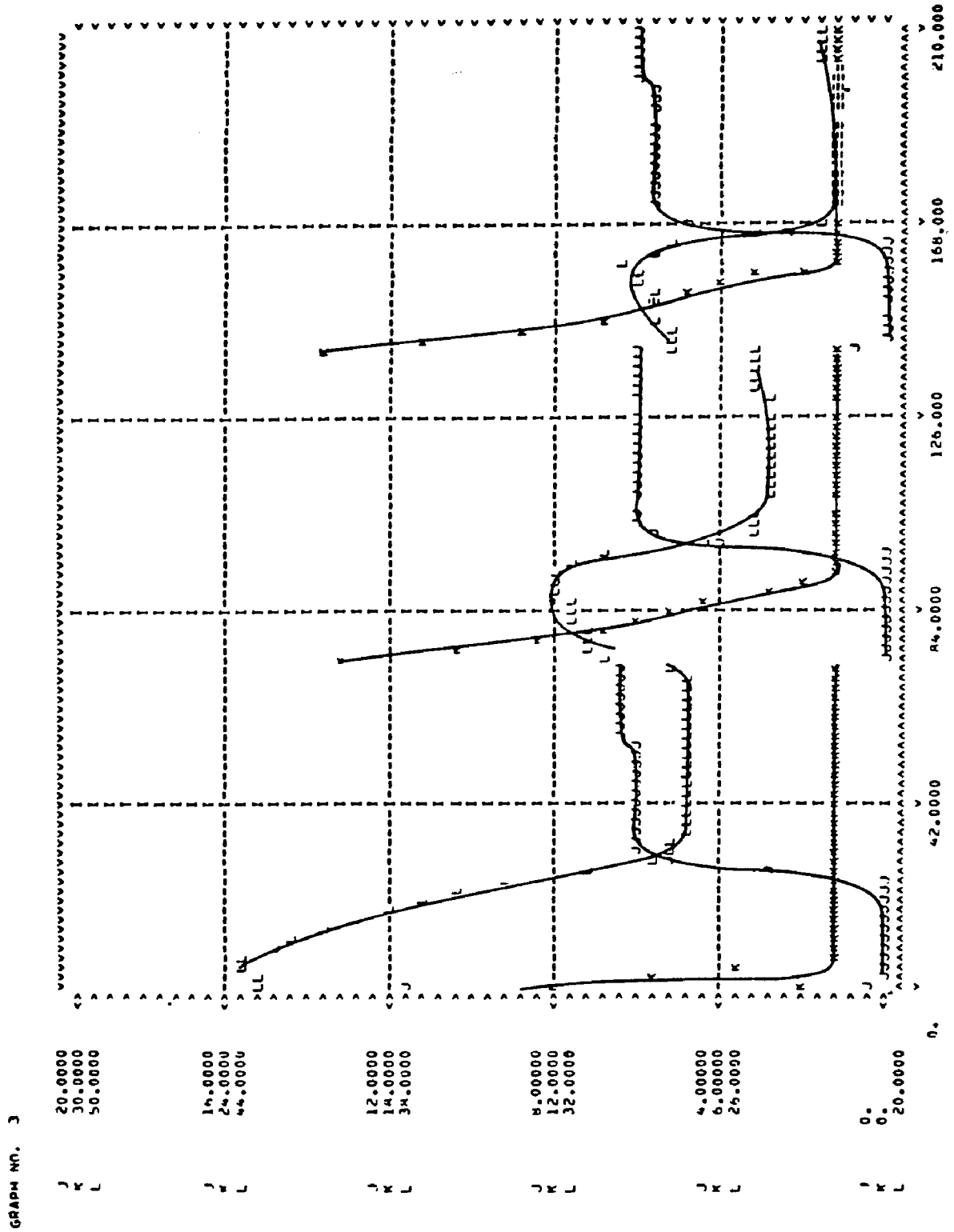
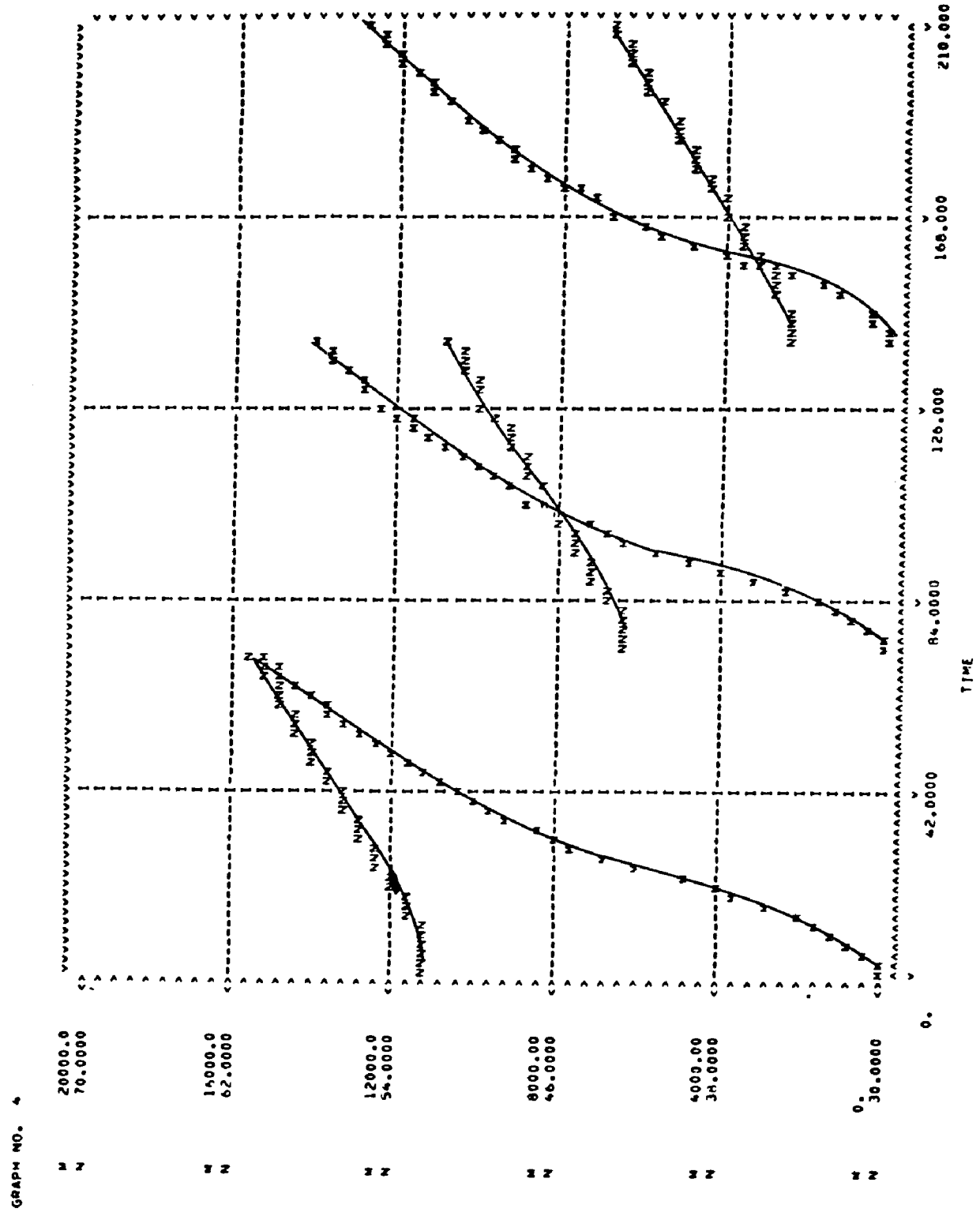

GRAPH NO. 3
J 20.0000
K 30.0000
L 50.0000
J 18.0000
K 24.0000
L 44.0000
J 12.0000
K 14.0000
L 34.0000
J 8.00000
K 12.0000
L 32.0000
J 4.00000
K 6.00000
L 26.0000
J 0.
K 0.
L 20.0000
0.
42.0000
84.0000
126.000
168.000
210.000
TIME

Figure 16. SIMCOMP simulation of total plant biomass (M=TPB) and total K (N=TOTK) in a lodgepole pine stand subjected to clearcutting (slash removed) three times at 70 year intervals. M and N are both in $g\ m^{-2}$ (oven dry weight).


GRAPH NO. 4
20000.0
70.0000
16000.0
62.0000
12000.0
54.0000
8000.00
46.0000
4000.00
38.0000
0.
30.0000
0.
42.0000
84.0000
126.000
168.000
210.000
TIME

Simulation Output 3. Numerical output for the simulation of forest growth and K cycling in a lodgepole pine forest subjected to clearcutting with slash removed from the system (time is in years and values are in g m^{-2}).

SIMULATION OUTPUT

TIME = 0.

X(1)	=	1.00000000	X(2)	=	0	X(3)	=	0	X(4)	=	0
X(5)	=	0	X(6)	=	0	X(7)	=	0	X(8)	=	0
X(10)	=	2769.40000	X(11)	=	1720.00000	X(12)	=	3875.00000	X(13)	=	0
X(14)	=	.103000000E-01	X(15)	=	0	X(16)	=	0	X(17)	=	0
X(18)	=	0	X(19)	=	0	X(20)	=	0	X(21)	=	0
X(23)	=	6.36962000	X(24)	=	3.10000000	X(25)	=	43.2000000	X(26)	=	0
X(27)	=	46.3000000	X(28)	=	1000.00000	X(29)	=	1000.00000	X(30)	=	1000.00000
X(98)	=	0	X(99)	=	1000.00000	TPH	=	0	TEMP	=	0
TOTK	=	52.6799200	TOTN	=	0						

TIME = 70.0000000

X(1)	=	220.497148	X(2)	=	220.428480	X(3)	=	220.362774	X(4)	=	126.672579
X(5)	=	519.145274	X(6)	=	1457.99687	X(7)	=	9022.45773	X(8)	=	3794.27725
X(10)	=	2685.20399	X(11)	=	686.406689	X(12)	=	187.554860	X(13)	=	292.060000
X(14)	=	2.27112053	X(15)	=	2.27041335	X(16)	=	2.26973657	X(17)	=	1.30472757
X(18)	=	1.34717771	X(19)	=	3.79079186	X(20)	=	5.41347464	X(21)	=	3.79427725
X(23)	=	6.60878437	X(24)	=	1.90000000	X(25)	=	30.7194161	X(26)	=	1.000000000
X(27)	=	29.7974719	X(28)	=	993.490000	X(29)	=	1000.00000	X(30)	=	996.500000
X(98)	=	.727545761E-11	X(99)	=	36557.9872	TPH	=	15461.0672	TEMP	=	668.173176
TOTK	=	61.5469200	TOTN	=	787.960981						

TIME = 140.000000

X(1)	=	203.211702	X(2)	=	203.083798	X(3)	=	202.959583	X(4)	=	116.632543
X(5)	=	476.423010	X(6)	=	1344.97556	X(7)	=	8321.01584	X(8)	=	3547.24542
X(10)	=	2469.67269	X(11)	=	671.997258	X(12)	=	186.908251	X(13)	=	484.120000
X(14)	=	2.09308053	X(15)	=	2.09176312	X(16)	=	2.09048371	X(17)	=	1.20131519
X(18)	=	1.23869983	X(19)	=	3.49691646	X(20)	=	4.99260950	X(21)	=	3.54724542
X(23)	=	6.04236507	X(24)	=	1.90000000	X(25)	=	23.4479789	X(26)	=	1.85000000
X(27)	=	22.7394881	X(28)	=	986.980000	X(29)	=	1000.00000	X(30)	=	993.000000
X(98)	=	.363797881E-11	X(99)	=	57675.3162	TPH	=	14305.5161	TEMP	=	615.793037
TOTK	=	52.0394777	TOTN	=	725.887626						

TIME = 210.000000

X(1)	=	183.403646	X(2)	=	183.201257	X(3)	=	183.002646	X(4)	=	105.114585
X(5)	=	424.162394	X(6)	=	1211.67558	X(7)	=	7479.54037	X(8)	=	3251.93753
X(10)	=	2214.65301	X(11)	=	643.594770	X(12)	=	193.931900	X(13)	=	676.180000
X(14)	=	1.88905755	X(15)	=	1.88697295	X(16)	=	1.88492725	X(17)	=	1.08268023
X(18)	=	1.11392222	X(19)	=	3.15035652	X(20)	=	4.48772422	X(21)	=	3.25193753
X(23)	=	5.47534242	X(24)	=	1.90000000	X(25)	=	18.0153285	X(26)	=	2.70000000
X(27)	=	17.5532104	X(28)	=	980.470000	X(29)	=	1000.00000	X(30)	=	989.500000
X(98)	=	.363797881E-11	X(99)	=	82407.9989	TPH	=	12926.0111	TEMP	=	555.768623
TOTK	=	43.9945893	TOTN	=	654.722134						

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APPENDIX A

Appendix A

Analyses of vegetation of the Douglas-fir and the spruce-fir stands described in the text (taken directly from the unpublished data of W. H. Moir).

Pseudotsuga menziesii/Jamesia americana (Sampling date - June 23, 1966).

Tree Density by Size Class Area to which figures apply: 375 M^2

Species	Diameter Breast Height					
	0 2"					
	Height			2-4"	4-8"	8-12"
	Seedlings	< 3'	> 3'			
Pinus ponderosa	0	0	2	1	4	
Pinus contorta			1		1	
Pseudotsuga menziesii	1	10	56	46	24	12

Ground Cover by cover and frequency.

Species	Cov/Freq.
Shrubs	
Jamesia americana	18/33
Physocarpus monogynus	1/ 7
Symphoricarpos allus	1/ 3
Rosa sp.	1/17
Juniperus communis	1/ 3
Acer glabrum	0/ 3
Shepherdia canadensis	(+)
Arctostaphylos uva-ursi	+

Species	Cov/Freq.
Herbs	
Pyrola secunda	0/ 2
Pyrola virens	(+)
Chimaphila umbellata	0/ 3
Arnica cordifolia	1/17
Smilacina racemosa	2/15
Aralia nudicaulis	(+)
Calypso bulbosa	(+)
Disporum trachycarpum	+
Fragaria americana	+
Fragaria ovalis	+
Corallorhiza maculata	+
Clematis sp.	+
Carex rossii	+
Lupinus argenteus	+
Potentilla spp.	+
Senecio wootoni	+
Solidago spathulata	0/ 3
Cryptogams	
Hypnum spp.	/58
Peltigera sp.	/12
Parmelia consparsa	/20

Picea engelmannii-Abies lasiocarpa/Vaccinium myrtillus (Sampling date - October 8, 1966).

Tree Density by Size Classes Area to which figures apply: 600 M^2

Species	Diameter Breast Height							
	0-6" Height			2-4"	4-8"	8-12"	12-16"	> 16"
	Seedlings	< 3'	> 3'					
Picea engelmannii	0	40	13	6	17	8	7	1
Abies lasiocarpa	1120	535	84	37	17	16	3	0

Ground cover by cover and frequency (reported for 3 10 x 20 m plots).

	Plot 1	Plot 2	Plot 3
Vaccinium myrtillus	76/100	69/100	74/100
Pyrola secunda		(+)	+
Gaultheria humifusa		(+)	
Cladonia coniocraea	2/ 36		
C. ecmocyna	4/ 44	3/ 72	29/ 44
C. pyxidata	2/ 44		
Peltigera aphthosa	1/ 4		
P. malacea	0/ 8		
mosses	22/ 61	4/ 44	24/ 66

APPENDIX B

Appendix B

Technical descriptions of soil profiles in the lodgepole pine, Douglas-fir 1 and 2, and spruce-fir stands are given below. With the exception of the Douglas-fir 2 stand (With one profile description) two typical profiles are described to illustrate the variability within small areas.

Lodgepole Pine Profile A

Horizon	Depth	Description
O1	3-1 cm	Leaves, twigs, and cones of lodgepole pine.
O2	1-0 cm	Decomposed OM mixed with fragments of mineral material; pH 4.6.
A1	0-3 cm	Dark brown (10 YR 3/3, dry) to black (YR 2/1, moist); charcoal present; gravelly loamy sand, 6% clay; structureless, single grained; non-sticky, non-plastic; pH 5.1; many small roots; abrupt wavy boundary; 1 to 5 cm thick.
A21	3-5 cm	Light yellow brown (10 YR 6/4 dry) to dark yellowish brown (10 YR 3/4 moist); gravelly loamy sand-sandy loam, 5% clay; structureless, single grained; non-sticky, non-plastic; pH 5.2; very high density of roots; abrupt broken boundary; 0 to 3 cm thick.
A22	5-22 cm	Brown (10 YR 5/3, dry) to dark yellowish brown (10 YR 3/4, moist); gravelly sandy

Horizon	Depth	Description
		loam, 7% clay; structureless, massive; non-sticky non-plastic; pH 5.5; fewer roots than above; diffuse wavy boundary; 15 to 3 30 cm thick.
A & B	22-53 cm	Light yellowish brown (10 YR 6/4, dry) to brown to dark brown (10 YR 4/3, moist); gravelly loamy sand, 6% clay; structureless, massive; non-sticky, non-plastic; pH 5.8; roots as in A22; diffuse wavy boundary; 15 to 30 cm thick.
B2t	53-79 cm	Yellowish brown (10 YR 5/4, dry) to dark yellowish brown (10 YR 4/4, moist); cobbly, gravelly, sandy loam, 12% clay; structureless, massive but including some small pockets that are weakly subangular blocky; non-sticky, non-plastic; pH 5.8; few roots present; much of the material is primary an and is in extremely advanced stages of weathering; gradual wavy boundary; 22 to 30 cm thick.
C	79 cm	Dark yellowish brown to reddish brown (10 YR 4/4 to 2.5 YR 4/4, dry) to reddish brown (2.5 YR 4/4, moist); cobbly, gravelly, sandy loam, 10% clay; structureless, single grained; non-sticky, non-plastic; pH 5.8; few roots; extremely weathered rock.

Lodgepole Pine Profile B

Horizon	Depth	Description
O1	2-0.5 cm	Leaves, twigs, cones, and bark flakes of lodgepole pine.
O2	0.5-0 cm	Decomposed debris of lodgepole pine mixed with noticeable amounts of mineral material.
A1	0-4 cm	Dark grayish brown (10 YR 4/2, dry) to very dark brown (10 YR 2/2, moist); charcoal present; gravelly, sandy loam, 7% clay; structureless, single grained; non-sticky, non-plastic; pH 4.8; numerous small roots; abrupt wavy boundary; 2 to 4 cm thick.
A21	4-19 cm	Light yellowish brown (10 YR 6/4, dry) to dark yellowish brown (10 YR 3/4, moist); gravelly, sandy loam, 7% clay; structureless, single grained or may be a very slight hint of a crumb texture; non-sticky, non-plastic; pH 5.1; highest density of roots in profile; clear wavy boundary; 13 to 20 cm thick.
A22	19-34 cm	Pale brown (10 YR 6/3, dry) to brown to dark brown; (10 YR 4/3, moist); sand grains appear much cleaner in this horizon; gravelly, sandy loam, 7% clay; structureless, single grained; non-sticky,

Horizon	Depth	Description
		non-plastic; pH 5.5; fewer and finer roots present; clear wavy boundary; 15 to 20 cm thick.
B21t	34-43 cm	Yellowish brown (10 YR 5/8, dry) to strong brown (7.5 YR 5/6, moist) containing a broken 1-3 cm thick band of dark reddish brown (5 YR 3/4, moist); gravelly, sandy clay loam, 21% clay; structureless, massive; plastic, slightly sticky; pH 5.6; a few tiny roots present; abrupt wavy boundary; 6 to 10 cm thick.
B22t	43-68 cm	Yellowish brown (10 YR 5/8, dry) to yellowish brown (10 YR 5/5, moist); gravelly, sandy clay loam to sandy loam, 20% clay; structureless, massive; slightly sticky, very slightly plastic; pH 5.6, a few tiny roots present; gradual to diffuse wavy boundary; much extremely decomposed but recognizable rock; 20 to 25 cm thick.
B3	68-89 cm	Brownish yellow to yellowish brown (10 YR 5.5/8, dry and moist); gravelly, sandy loam to sandy clay loam; 20% clay; structureless, single grained; very slightly sticky, non-plastic to very slightly plastic, pH 5.9; occasional roots but very few; diffuse wavy boundary; 25 to 35 cm thick.

Horizon	Depth	Description
C	89 - cm	Brownish yellow to yellowish brown (10 YR 5.5/8, dry) to yellow (10 YR 7/8, moist); gravelly, sandy loam, 10% clay; structureless, single grained; non-sticky, non-plastic; pH 6.0; occasional roots.

Douglas-fir 1 Profile A

Horizon	Depth	Description
O11	2.5-0.5 cm	Distinct needles, twigs, cones, and bark fragments of Douglas-fir with some needles of Pinus ponderosa.
O12	0.5-0 cm	Material as above but in more advanced stage of decomposition. Fragments recognizable with the naked eye.
A1	0-2 cm	Very dark grayish brown (10 YR 3/2, dry) to black (10 YR 2/1, moist); dark color due, in part, to charcoal; cobbly, gravelly sandy loam, 9% clay; Structureless, single grained; loose; pH 5.5; numerous small roots; a distinct large gravel and cobble line between A1 and A2; abrupt wavy boundary; 2 to 5 cm thick.
A2	2-10 cm	Light yellowish brown (10 YR 6/4, dry) to brown (10 YR 4/3.5, moist); cobbly, gravelly sandy loam, 7% clay; structureless, single grained; loose; pH 5.0; numerous large and small roots; clear, wavy boundary; 7 to 10 cm thick.
A3	10-21 cm	Light yellowish brown (10 YR 6/4, dry) to dark yellowish brown (10 YR 4/4, moist); structureless, single grained; loose; inclusions and tongues of dark reddish

Horizon	Depth	Description
		brown (5 YR 3/3, moist); cobbly, gravelly, sandy loam, 4% clay; structureless, single grained, some very friable material noted here and in B1; pH 5.1; most small roots in this horizon; abrupt, irregular boundary; 10 to 16 cm thick.
B1	21-43 cm	Light yellowish brown (10 YR 6/4, dry) to yellowish brown (10 YR 5/4, moist); cobbly, gravelly, sandy loam, 4% clay; structureless, single grained; loose; pH 4.9; a few large and small roots present; clear, irregular boundary; 14 to 20 cm thick.
B2	43-50 cm	Light brown (7.5 YR 6/4, dry) to yellowish brown (10 YR 5/5, moist); cobbly, gravelly loamy sand, 5% clay; structureless, single grained; very friable; pH 5.1; a few pencil-sized roots present; clear, wavy boundary; 5 to 8 cm thick.
C	50 + cm	Reddish yellowish brown (8.75 YR 5/6, dry) to yellowish brown (10 YR 5/8, moist); very coarse, only extremely weathered rock; pH 5.4.

Douglas-fir 1 Profile B

Horizon	Depth	Description
O1	4-2 cm	Distinct needles, twigs, and bark fragments of Douglas-fir trees
O2	2-0 cm	Needles, twigs, and bark fragments in advanced stages of decomposition; some mineral particles are present.
A11	0-4 cm	Very dark grayish brown (10 YR 3/2, dry) to black (10 YR 2/1, moist); dark color partly caused by abundant charcoal; very cobbly, gravelly sandy loam, 8% clay; structureless, single grained; loose; pH 6.5; many small roots; partially decomposed wood fragments present; abrupt, wavy bound boundary; 1 to 5 cm thick.
A12	4-6 cm	Black (7.5 YR 2/0, moist) with abundant charcoal present; very cobbly, gravelly sandy loam; structureless, single grained; loose; many small roots; abrupt, broken boundary; 0 to 2 cm thick but mostly less than 1 cm. NOT SAMPLED.
A2	6-15 cm	Grayish brown to brown (10 YR 5/2.5, dry) to brown to dark brown (10 YR 4/3, moist); cobbly, gravelly loamy sand, 4% clay; structureless, single grained; loose; pH 4.5; both large and small roots present;

Horizon	Depth	Description
		60 to 75% of the volume is cobbles and stones which comprise a more or less distinct layer. Elluviation is apparent between the stones and to a depth of about 10 cm below; gradual, wavy boundary; 6-13 cm thick.
A & B	15-56 cm	Yellowish brown (10 YR 5/4, dry) to yellowish brown to dark yellowish (10 YR 4.5/4, moist), pockets of yellowish brown (10 YR 5/5, moist) included; cobbly, gravelly loamy sand, 3% clay; structureless, single grained; loose; pH 5.3; some small roots and many large roots; fewer stones and cobbles present than in upper horizons; clear, irregular boundary; 30-41 cm thick.
B21t	56-62 cm	Yellowish brown (10 YR 5/5, dry and moist); cobbly, gravelly loamy sand, 5% clay; structureless, single grained; very friable; pH 5.2; few roots present; abrupt wavy boundary; 5 to 15 cm thick.
B22t	62-81 cm	Light yellowish brown to yellowish brown (10 YR 5.5/4, dry) to yellowish brown to dark yellowish brown (10 YR 4.5/5, moist); cobbly, gravelly loamy sand, 6% clay; structureless, single grained; very friable;

Horizon	Depth	Description
		pH 5.4; occasional roots present; abrupt, wavy boundary; 15 to 23 cm thick.
B23t	81-91 cm	Strong brown (7.5 YR 5/8, dry) to strong brown (7.5 YR 5/6, moist) banded with yellowish brown (10 YR 5/8, moist); cobbly, gravelly sandy-loam, 16% clay; structureless and massive moist but appears weakly subangular blocky dry; firm; pH 5.4; no roots; abrupt, wavy boundary; 8 to 15 cm thick.
C	91 - cm	Yellowish brown (10 YR 5/6, dry and moist); cobbly, gravelly loamy sand, 8% clay; structureless and single grained; very friable when moist; pH 5.6; no roots.

Douglas-fir 2 Profile A

Horizon	Depth	Description
O11	4-3 cm	Debris from both overstory and understory plants that has accumulated in the last year; 1 to 2 cm thick.
O12	3-1 cm	Decomposed but recognizable remains of leaves, twigs, cones and bark. 1 to 2 cm thick.
O2	1-0 cm	Decomposed OM mixed with lenses of mineral material; strong mycorrhizal activity; abrupt, wavy boundary.
A1	0-11 cm	Dark grayish brown (10 YR 4/2, dry) to very dark brown (10 YR 2/2, moist); cobbly, gravelly loamy sand, 5% clay; structureless, single grained; loose to very friable; pH 5.4; abundant mycorrhizas and numerous roots present especially in old decomposed root channels; abrupt, wavy boundary; 6 to 12 cm thick.
A21	11-12 cm	Brown (10 YR 5/3, moist); cobbly, gravelly loamy sand; structureless, single grained; loose; appears as lenses, sometimes just below the O2; abrupt, broken boundary; 0 to 2 cm thick. Pooled with A22.
A22	12-22 cm	Light yellowish brown (10 YR 6/2, dry) to dark brown (10 YR 3/3, moist); cobbly,

Horizon	Depth	Description
		gravelly sand, 4% clay; structureless, very weak massive or very weak crumb (apparent structure may be caused by fine roots and hyphae); loose; pH 5.3; more roots than below, may be only distinguishing feature from below; diffuse wavy boundary; 8 to 13 cm thick.
B2	22-41 cm	Pale brown (10 YR 6/3, dry) to brown to dark brown (10 YR 4/3, moist); cobbly, gravelly loamy sand, 4% clay; structureless, single grained; loose; pH 5.2; few roots; irregular abrupt boundary due to large boulders.
R	41 + cm	

Spruce-Fir Profile A

Horizon	Depth	Description
O11	10-6 cm	Leaves, twigs, and debris from spruce, fir and Vaccinium myrtillus; 2 to 5 cm thick.
O12	6-2 cm	Mostly rotten wood from a fallen log; 0 to 5 cm thick.
O2	2-0 cm	Decomposed OM of unknown origin; very distinct under the rotten log but not around pit where log absent; 0 to 3 cm thick.
A2	0-5 cm	Pinkish gray to brown (7.5 YR 5.5/2, dry) to brown to dark brown (10 YR 4.5/3, moist); cobbly, gravelly sandy loam, 10% clay; structureless, single grained; loose; pH 3.9; few roots present; abrupt wavy boundary; 1 to 10 cm thick.
B1	5-13 cm	Pale brown to brown (10 YR 5.5/3, dry) to dark yellowish brown (10 YR 4/4, moist); cobbly, gravelly sandy loam, 14% clay; structureless, massive to very weak crumb; very friable; pH 4.3; density of roots highest of profile; clear, wavy boundary; 4 to 13 cm thick,
B21t	13-24 cm	Yellowish brown (10 YR 5/6, dry) to dark reddish brown (5 YR 3/4, moist); cobbly, gravelly sandy loam, 9% clay; structureless, massive; very friable; pH 4.4; few

Horizon	Depth	Description
		roots present; diffuse wavy boundary; 8 to 20 cm thick.
B22t	24-38 cm	Brownish yellow to yellowish brown (10 YR 5.5/6, dry) to strong brown (7.5 YR 4/5, moist); cobbly, gravelly sandy clay loam, 28% clay; structureless, massive; very friable; very few roots; diffuse wavy boundary; 10 to 20 cm thick.
B3	38-48 cm	Light yellowish brown to yellowish brown (10 YR 6.5/5) to strong brown (7.5 YR 5/6, moist); gravelly sandy loam, 9% clay; structureless, single grained; very friable; pH 4.9; very few roots; diffuse wavy boundary; 5 to 15 cm thick.
C	48 - cm	This horizon is highly streaked and mottled with the dominant colors being brownish yellow (10 YR 6.5/5, dry) and light olive brown (2.5 YR 5/6, moist) and olive brown (2.5 YR 4/4, moist); cobbly, gravelly sandy loam, 7% clay; structureless, single grained; loose; pH 5.2; no roots.

Spruce-Fir Profile B

Horizon	Depth	Description
O1	1-0.5 cm	Litter of trees and Vaccinium myrtillus mixed with moss; 0.5 to 1 cm thick.
O2	0.5-0 cm	Decomposed debris from above; 0.25 to 0.5 cm thick.
A2	0.12 cm	Light gray to light brownish gray (10 YR 6.5/2, dry) to brown (10 YR 5/3, moist); cobbly, gravelly sandy loam, 6% clay; structureless, single grained; loose; pH 3.8; numerous roots; abrupt irregular boundary; 10 to 13 cm thick.
B21t	12-20 cm	Strong brown (7.5 YR 4.5/5, dry) to reddish brown to dark reddish (5 YR 3.5/4, moist); cobbly, gravelly sandy clay loam; 22% clay; structureless, massive; very friable; numerous small roots present; clear, irregular boundary; 5 to 10 cm thick.
B22	20-36 cm	Yellowish brown (10 YR 5/8, dry) to strong brown (7.5 YR 4.5/6, moist); cobbly, gravelly sandy loam, 9% clay; structureless, massive to single grained; very friable; pH 4.6; fewer roots than above; clear wavy boundary; 15 to 33 cm thick.
C	36 - cm	This horizon is highly streaked and mottled with the dominant colors being brownish

Horizon	Depth	Description
		yellow (10 YR 6.5/6, dry) and light olive brown (2.5 YR 5/3, dry) to yellowish brown (10 YR 5/6, moist) to olive brown (2.5 YR 4/4, moist); cobbly, gravelly sandy loam, 6% clay; structureless, single grained; loose; pH 4.6; occasional roots.

APPENDIX C

Appendix C

Determination of State Variables

State Variables	Source	Units	Comments
X(1), X(2), X(3), X(4)	Moir and Grier (1969) Moir and Francis (1972)	gm^{-2} of OM (organic matter)	Annual production of needles at maturity is about 235 gm^{-2} and total needle biomass is about 840 gm^{-2}.
X(5), X(6), X(7)	Moir (1972)	gm^{-2} OM	Living and dead twigs are combined as are stem wood and bark.
X(8)	Rodin and Bazelivich (1967)	gm^{-2} OM	Roots are assumed to contain 25% of total plant biomass.
X(10)	Moir and Grier (1969)	gm^{-2} OM	All humus horizons of the forest floor (not including the All horizon)
X(11)	Unpublished data of R. G. Woodmansee, Lutz and Chandler (1946), and Buckman and Brady (1969)	gm^{-2} OM	Mean carbon value for the <2mm fraction were corrected for bulk density (0.7), depth of horizon (3.0 cm), percentage of gravel (20), and percentage of rock (10). The resulting value was multiplied by 1.58 to give OM.
X(12)	As in X(11)	gm^{-2} OM	Mean carbon values for the <2mm fraction were corrected for bulk density (1.5), combined depth of A2 and B horizons (53.0 cm), percentage of gravel (30), and percentage of rock (10). The resulting value was multiplied by 1.58 to give OM.
X(14), X(15), X(16), X(17)	Unpublished data of W. H. Moir	gm^{-2} K (potassium)	K content of needles was 1.03% ODW and did not vary with age.

Table State Variables	Source	Units	Comments
X(18)	Rodin and Bazelivich (1967)	gm^{-2} K	Cones were assumed to have the same K concentration as young stems with the lower concentrations of the woody portions offset by the higher concentrations of the seeds.
X(19), X(20)	Rodin and Bazelivich (1967)	gm^{-2} K	Values for other species of pines.
X(21)	Rodin and Bazelivich (1967)	gm^{-2} K	Assumed to have concentrations of K intermediate between stems and trunks.
X(23)	Moir and Grier (1969)	gm^{-2} K	Does not include A11 horizon.
X(24), X(25)	Unpublished data of R. G. Woodmansee	gm^{-2} K	Mean K values were corrected in a similar as discussed in X(11) and X(12).
X(28), X(29), X(30)		gm^{-2} K	Infinite pools and sinks (set at 1000 to implement program).
X(98)	Rodin and Bazelivich (1967), Moir and Francis (1972) and Moir (1972)	gm^{-2} OM	Discussed in (99, 98). of section Derivation of the Model.
X(99)		gm^{-2} K	Infinite pool and sink (set at 1000 to implement the program).

APPENDIX D

Appendix D. SIMCOMP program for the fire-maintained system.

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SIMCOMP VERSION 2.0          06/16/72                    09.05.27.          PAGE NO.  1

                COMMON/A/FKIN,FKICT,FKIR,FKIL,FKIP,
               *EFK, FNGFT (15), TPH,FCGFT(15), AGE,
               *TSLH, FTGFT(15), FHGFT(15),FRGFT(15),
               *CLR, TLR, SLR, RLR, RLA1, RA1A2, DECR1,DECR2,
               *TEMP,TEMPN,TEMPC,TEMPT,TEMPH,TEMPR, TEMP27 ,
               *FEFT(15),FLFT(15),FEOFT(15),ERODE,ERODO,LEACH ,TOTK,TOTN
              (1,2), F=X(1)/DT
              (2,3), F=X(2)/DT
              (3,4), F=.575*X(3)/DT
              (3,10), F=.425*X(3)/DT
              (4,10), F=X(4)/DT
              (5,10), F=X( 5)*CLIP(0.,CLR,25.,AGE)
                   TEMP5=F
              (6,10), F=X(6)*CLIP(0.,TLR,25.,AGE)
                   TEMP6=F
              (6,99),F=.01 *X(6)
              (7,10), F=X(7)*CLIP(0.,SLR,25.,AGE)
                   TEMP7=F
              (7,99),F=.019*X(7)
              (8,11), F=.25*X(8)*RLR
                   TEMP8=F/.25
              (8,12), F=.75*X(8)*RLR
              (10,11), F=RLA1*X(10)
              (10,13), F=0.
              (10,99),F=CLIP((X(10)+X(4)+.425*X(3))/DT+.1*X(10)/DT,25.,AGE)
                   TEMP10=F
              (11,12), F=RA1A2*X(11)
              (11,13),F=ERODO
              (11,99),F=CLIP(.06*X(11)+.2*X(11)+720.,X(11))
              (12,99),F=CLIP(.06*X(12)+.2*X(12)+185.,X(12))
              (14,15), F=X(14)/DT
              (15,16), F=X(15)/DT
              (16,17), F=.575*X(16)/DT
              (16,21), F=.425*X(16)/DT
              (17,23), F=X(17)/DT
              (18,23), F=FKICT*TEMP5
              (19,23), F=FKICT*TEMP6 +.01*.0026*X (6)
              (20,23),F=FKIR*TEMP7  +.019*.0006*X(7)
              (21,24), F=FKIN*TEMPR*.25
              (21,25), F=FKIN*TEMPR*.75
              (23,24),F=CLIP(.95*(X(17)+.425*X(16)) +.95*X(23)       /DT+.4*X(23),25.,
                  *AGE)
              (24,25),F=LEACH
              (24,30),F=ERODE
              (25,29),F=LEACH
              (27,14), F=FKIN*TEMPN
              (27,18), F=FKICT*TEMPC
              (27,19), F=FKICT*TEMPT
              (27,20), F=FKIR*TEMPR
              (27,21), F=FKIR*TEMPR
              (28,29),F=0.093
              (30,24), F=0.05
              (99,1),F=TEMPN
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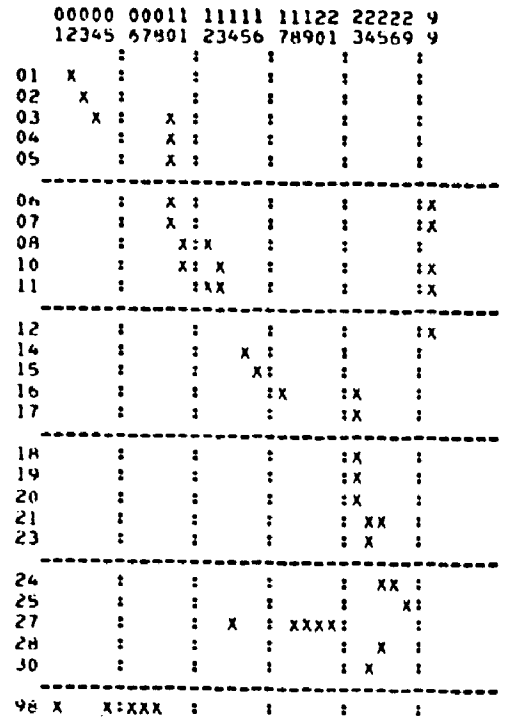
```
          (98,5),F=TEMPC
   55     (98,6),F=TEMPT
          (98,7),F=TEMPB
          (98,8),F=TEMPR
          C*************************************************************************
                SUBROUTINE START
   60           X(14)=FKIN*X(1)
                X(15)=FKIN*X(2)
                X(16)=FKIN*X(3)
                X(17)=FKIN*X(4)
                X(18)=FKICT*X(5)
   65           X(19)=FKICT*X(6)
                X(20)=FKIN*X(7)
                X(21)=FKIN*X(8)
                X(23)=FKIL*X(10)
                 X(27) = X(24)+X(25)
   70           TOTK=X(14)+X(15)+X(16)+X(17)+X(18)+X(19)+X(20)+X(21)+X(23)+
               *X(24)+X(25)
                RETURN
                END
          C*************************************************************************
   75           SUBROUTINE CYCLI
                IF(TIME.EQ.70.)1,2
              1 TSLH=70.
                X(24)=X(24)+X(14)+X(15)+X(16)+X(17)+X(18)+X(19)+X(20)+X(23)+
               *.25*X(21)
   80           X(25)=.75*X(21)+X(25)
                X(11)=X(11)+.25*X(8)
                X(12)=X(12)+.75*X(8)
                X(1)=1.
                TPR=0.
   85           X(20)=0.
                X(2)=X(3)=X(4)=X(5)=X(6)=X(7)=X(8)=X(10)=0.
                X(14)=X(15)=X(16)=X(17)=X(18)=X(19)=      X(21)=0.
                X(23) =0.
              2 IF(TIME.EQ.140.)4,3
   90         4 TSLH=140.
                X(11)=X(11)+.25*X(8)
                X(12)=X(12)+.75*X(8)
                X(24)=X(24)+X(14)+X(15)+X(16)+X(17)+X(18)+X(19)+X(20)+X(23)+
               *.25*X(21)
   95           X(25)=.75*X(21)+X(25)
                X(1)=1.
                X(14)=X(15)=X(16)=X(17)=X(18)=X(19)=      X(21)=0.
                X(23) =0.
                X(20)=0.
  100           X(2)=X(3)=X(4)=X(5)=X(6)=X(7)=X(8)=X(10)=0.
                TPR=0.
              3 ERODE=TABLE(FLFT,AGE,0.,7.,1.)
                LEACH=TABLE(FLFT,AGE,0.,7.,1.)
                ERODO=TABLE(FLOFT,AGE,0.,6.,1.)
  105           TPR=X (1)+X(2)+X(3)+X(4)+X(5)+X(6)+X(7)+X(8)
                AGE=TIME-TSLH
```

```
      TOTK=X(14)+X(15)+X(16)+X(17)+X(18)+X(19)+X(20)+X(21)+X(23)+
     *X(24)+X(25)
      X(27)=X(24)+X(25)
110   TEMP27 = X(27)
      FK= (1.-EXP(EFK*X(27)))
      IF(X(27).LE.1.) FK =0.
      TEMP = GFA(AGE)*FK
      TEMPR=      TABLE(FRGFT,TPR,0.,16800.,1200.)
115   TEMPR=      TABLE(FBGFT,TPB,0.,16800.,1200.)
      TEMPT=      TABLE(FTGFT,TPH,0.,16800.,1200.)
      TEMPC=      TABLE(FCGFT,TPB,0.,16800.,1200.)
      TEMPN =     TABLE(FNGFT,TPH,0.,16800.,1200.)
      A = TEMPN +TEMPC+TEMPT+TEMPH+TEMPR
120   TEMPN = TEMPN*TEMP/A
      TEMPC = TEMPC*TEMP/A
      TEMPT = TEMPT*TEMP/A
      TEMPR = TEMPH*TEMP/A
      TEMPR = TEMPR*TEMP/A
125   X(9R) = TEMP
      RETURN
      END
C*****************************************************************************
      SUBROUTINE CYCL2
130   TOTN=X(1)+X(2)+X(3)+X(4)
      A = TEMP27 - X(27)
      IF((X(24)-1.9).GT.    A)1,2
    1 X(24)=X(24)-   A
      GO TO 3
135   2 X(25)=X(25)-(A-(X(24)-1.9))
      X(24)=1.9
    3 CONTINUE
      RETURN
      END
140 C*****************************************************************************
      FUNCTION GFA(Y)
      DIMENSION A(15)
      DATA (A(I),I=1,15)/0.,.225,.405,.565,.718,.750,.750,.750,.750,.
     *750,.750,.750,.750,.750,.750,.750,./
145   IF(Y.LE.0.) 1,2
    1 GFA=A(1)
      RETURN
    2 IF(Y.GE.70.) 3,4
    3 GFA=A(15)
150   RETURN
    4 I=Y/5.+1.
      GFA=(A(I+1)-A(I))/5.*(Y-(I-1)*5.)+A(I)
      RETURN
      END
155 C*****************************************************************************
      FUNCTION TABLE (A,B,C,D,E)
      DIMENSION A(15)
      IF (C.LE.C)1,2
    1 TABLE = A(1)
```

```
      RETURN
    2 IF (B.GE.D) 3,4
    3 TABLE = A(15)
      RETURN
    4 K = (B-C)/E
      I = K+1
      J = I+1
      TABLE = (A(J)-A(I))/E*(B-C-K*E)+A(I)
      RETURN
      END
C*****************************************************************************
      FUNCTION CLIP (A,B,C,D)
      CLIP = A
      IF (D.GE.C) CLIP = B
      RETURN
      END
```


00000 00011 11111 11122 22222 9
12345 67891 23456 78901 34569 9
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PROGRAM CHARACTERISTICS 06/16/72 09.05.27.

30	STATE VARIABLES
45	FUNCTIONS
1	DECLARED COMMON BLOCKS
37	USER DECLARED VARIABLES
149	AMOUNT OF USER DECLARED STORAGE
14.500	FIRST PASS COMPILATION TIME(SEC)

STATE VARIABLE LIST -

1	2	3	4	5	6	7	8	10	11
12	13	14	15	16	17	18	19	20	21
23	24	25	26	27	28	29	30	98	99

LIST OF FUNCTION LABELS -

102	203	304	310	410
510	610	699	710	799
811	812	1011	1013	1099
1112	1113	1199	1299	1415
1516	1617	1623	1723	1823
1923	2023	2124	2125	2324
2425	2426	2529	2714	2718
2719	2720	2721	2825	3024
9801	9805	9806	9807	9808

PARAMETER VALUES

COMMON/A /

FKIN	=	.103000000E-01	FKICT	=	.260000000E-02	FKIR	=	.100000000E-02	FKIL	=	.230000000E-02
FKIB	=	.600000000E-03	EFK	=	-.680000000E-01	FNGFT(1)	=	0	FNGFT(2)	=	.310000000
FNGFT(3)	=	.340000000	FNGFT(4)	=	.350000000	FNGFT(5)	=	.320000000	FNGFT(6)	=	.330000000
FNGFT(7)	=	.330000000	FNGFT(8)	=	.330000000	FNGFT(9)	=	.330000000	FNGFT(10)	=	.330000000
FNGFT(11)	=	.330000000	FNGFT(12)	=	.330000000	FNGFT(13)	=	.330000000	FNGFT(14)	=	.330000000
FNGFT(15)	=	.330000000	TPH	=	0	FCGFT(1)	=	0	FCGFT(2)	=	0
FCGFT(3)	=	0	FCGFT(4)	=	.700000000E-01	FCGFT(5)	=	.700000000E-01	FCGFT(6)	=	.700000000E-01
FCGFT(7)	=	.700000000E-01	FCGFT(8)	=	.700000000E-01	FCGFT(9)	=	.700000000E-01	FCGFT(10)	=	.700000000E-01
FCGFT(11)	=	.700000000E-01	FCGFT(12)	=	.700000000E-01	FCGFT(13)	=	.700000000E-01	FCGFT(14)	=	.700000000E-01
FCGFT(15)	=	.700000000E-01	AGE	=	INDEFINITE	TSLN	=	0	FTGFT(1)	=	0
FTGFT(2)	=	.800000000E-01	FTGFT(3)	=	.800000000E-01	FTGFT(4)	=	.100000000	FTGFT(5)	=	.900000000E-01
FTGFT(6)	=	.900000000E-01	FTGFT(7)	=	.900000000E-01	FTGFT(8)	=	.900000000E-01	FTGFT(9)	=	.900000000E-01
FTGFT(10)	=	.900000000E-01	FTGFT(11)	=	.900000000E-01	FTGFT(12)	=	.900000000E-01	FTGFT(13)	=	.900000000E-01
FTGFT(14)	=	.900000000E-01	FTGFT(15)	=	.900000000E-01	FBGFT(1)	=	0	FBGFT(2)	=	.200000000
FBGFT(3)	=	.390000000	FBGFT(4)	=	.360000000	FBGFT(5)	=	.370000000	FBGFT(6)	=	.370000000
FBGFT(7)	=	.400000000	FBGFT(8)	=	.400000000	FBGFT(9)	=	.400000000	FBGFT(10)	=	.400000000
FBGFT(11)	=	.400000000	FBGFT(12)	=	.400000000	FBGFT(13)	=	.400000000	FBGFT(14)	=	.400000000
FBGFT(15)	=	.400000000	FRGFT(1)	=	0	FRGFT(2)	=	.390000000	FRGFT(3)	=	.170000000
FRGFT(4)	=	.110000000	FRGFT(5)	=	.110000000	FRGFT(6)	=	.110000000	FRGFT(7)	=	.110000000
FRGFT(8)	=	.110000000	FRGFT(9)	=	.110000000	FRGFT(10)	=	.110000000	FRGFT(11)	=	.110000000
FRGFT(12)	=	.110000000	FRGFT(13)	=	.110000000	FRGFT(14)	=	.110000000	FRGFT(15)	=	.110000000
CLR	=	.900000000E-01	TLR	=	.260000000E-01	SLR	=	.210000000E-02	RLR	=	.100000000E-01
RLA1	=	.200000000E-01	RA1A2	=	.250000000E-02	DECK1	=	INDEFINITE	DECK2	=	INDEFINITE
TEMP	=	0	TEMPN	=	INDEFINITE	TEMPC	=	INDEFINITE	TEMPT	=	INDEFINITE
TEMPA	=	INDEFINITE	TEMPB	=	INDEFINITE	TEMP27	=	INDEFINITE	FEFT(1)	=	.150000000
FEFT(2)	=	.300000000	FEFT(3)	=	.150000000	FEFT(4)	=	.100000000	FEFT(5)	=	.800000000E-01
FEFT(6)	=	.500000000E-01	FEFT(7)	=	.200000000E-01	FEFT(8)	=	0	FEFT(9)	=	0
FEFT(10)	=	0	FEFT(11)	=	0	FEFT(12)	=	0	FEFT(13)	=	0
FEFT(14)	=	0	FEFT(15)	=	0	FLFT(1)	=	2.00000000	FLFT(2)	=	2.00000000
FLFT(3)	=	1.80000000	FLFT(4)	=	1.50000000	FLFT(5)	=	1.50000000	FLFT(6)	=	1.00000000
FLFT(7)	=	.800000000	FLFT(8)	=	.600000000	FLFT(9)	=	.100000000	FLFT(10)	=	.100000000
FLFT(11)	=	.100000000	FLFT(12)	=	.100000000	FLFT(13)	=	.100000000	FLFT(14)	=	.100000000
FLFT(15)	=	.100000000	FEOFT(1)	=	100.000000	FEOFT(2)	=	50.0000000	FEOFT(3)	=	25.0000000
FEOFT(4)	=	17.0000000	FEOFT(5)	=	.600000000E-01	FEOFT(6)	=	0	FEOFT(7)	=	0
FEOFT(8)	=	0	FEOFT(9)	=	0	FEOFT(10)	=	0	FEOFT(11)	=	0
FEOFT(12)	=	0	FEOFT(13)	=	0	FEOFT(14)	=	0	FEOFT(15)	=	0
ERODE	=	INDEFINITE	ERODO	=	INDEFINITE	LEACH	=	INDEFINITE	TOTK	=	INDEFINITE
TOTN	=	0									

STATE VARIABLES - INITIAL VALUES

X(1) =	1.00000000	X(2) =	0	X(3) =	0	X(4) =	0
X(5) =	0	X(6) =	0	X(7) =	0	X(8) =	0
X(10) =	0	X(11) =	1720.00000	X(12) =	3875.00000	X(13) =	0
X(14) =	INDEFINITE	X(15) =	INDEFINITE	X(16) =	INDEFINITE	X(17) =	INDEFINITE
X(18) =	INDEFINITE	X(19) =	INDEFINITE	X(20) =	INDEFINITE	X(21) =	INDEFINITE
X(23) =	INDEFINITE	X(24) =	33.1000000	X(25) =	37.1000000	X(26) =	0
X(27) =	INDEFINITE	X(28) =	1000.00000	X(29) =	1000.00000	X(30) =	1000.00000
X(98) =	0	X(99) =	1000.00000				

TIME PARAMETERS -

TSTART - 0.
TEND - 210.000000
DT - 1.00000000
DTPR - 70.0000000
DTPL - 0.
DTFL - 1.00000000

APPENDIX E

APPENDIX E

E. 1 Initial conditions and updates of the fire-maintained system.

STATE VARIABLES - INITIAL VALUES

```
X( 1)  =  1.00000000     X( 2)  =           0     X( 3)  =           0     X( 4)  =           0
X( 5)  =           0     X( 6)  =           0     X( 7)  =           0     X( 8)  =           0
X(10)  =           0     X(11)  =  1720.00000     X(12)  =  3875.00000     X(13)  =           0
X(14)  =  INDEFINITE     X(15)  =  INDEFINITE     X(16)  =  INDEFINITE     X(17)  =  INDEFINITE
X(18)  =  INDEFINITE     X(19)  =  INDEFINITE     X(20)  =  INDEFINITE     X(21)  =  INDEFINITE
X(23)  =  INDEFINITE     X(24)  =   33.1000000    X(25)  =   37.1000000    X(26)  =           0
X(27)  =  INDEFINITE     X(28)  =   1000.00000    X(29)  =   1000.00000    X(30)  =   1000.00000
X(98)  =           0     X(99)  =   1000.00000
```

MAIN PROGRAM

```
25          (10,99),F=CLIP((X(10)+X(4)+.425*X(3))/DT,.1*X(10)/DT,25.,AGE)
```

PARAMETER VALUES

```
FEFT(2)  =  .300000000     FEFT(3)  =  .150000000     FEFT(4)  =  .100000000     FEFT(1)  =  .150000000
FEFT(6)  =  .500000000E-01 FEFT(7)  =  .200000000E-01 FEFT(8)  =           0     FEFT(5)  =  .800000000E-01
FEFT(10) =           0     FEFT(11) =           0     FEFT(12) =           0     FEFT(9)  =           0
FEFT(14) =           0     FEFT(15) =           0     FLFT(1)  =  2.00000000     FEFT(13) =           0
FLFT(3)  =  1.80000000     FLFT(4)  =  1.50000000     FLFT(5)  =  1.50000000     FLFT(2)  =  2.00000000
FLFT(7)  =  .800000000     FLFT(8)  =  .600000000     FLFT(9)  =  .100000000     FLFT(6)  =  1.00000000
FLFT(11) =  .100000000     FLFT(12) =  .100000000     FLFT(13) =  .100000000     FLFT(10) =  .100000000
FLFT(15) =  .100000000                                                           FLFT(14) =  .100000000
```

SUBROUTINE CYCL1

```
      IF(TIME.EQ.70.)1,2
    1 TSLH=70.
      X(24)=X(24)+X(14)+X(15)+X(16)+X(17)+X(18)+X(19)+X(20)+X(23)+
     *.25*X(21)
   80 X(25)=.75*X(21)+X(25)
      X(11)=X(11)+.25*X(8)
      X(12)=X(12)+.75*X(8)
      X(1)=1.
      TPH=0.
   85 X(20)=0.
      X(2)=X(3)=X(4)=X(5)=X(6)=X(7)=X(8)=X(10)=0.
      X(14)=X(15)=X(16)=X(17)=X(18)=X(19)=       X(21)=0.
      X(23) =0.
    2 IF(TIME.EQ.140.)4,3
   90 4 TSLH=140.
      X(11)=X(11)+.25*X(8)
      X(12)=X(12)+.75*X(8)
      X(24)=X(24)+X(14)+X(15)+X(16)+X(17)+X(18)+X(19)+X(20)+X(23)+
     *.25*X(21)
   95 X(25)=.75*X(21)+X(25)
      X(1)=1.
      X(14)=X(15)=X(16)=X(17)=X(18)=X(19)=       X(21)=0.
      X(23) =0.
      X(20)=0.
  100 X(2)=X(3)=X(4)=X(5)=X(6)=X(7)=X(8)=X(10)=0.
      TPH=0.
```

E. 2 Initial conditions and updates of the clearcut, slash left to decompose as litter treatment.

STATE VARIABLES - INITIAL VALUES

X(1) =	1.00000000	X(2) =	0	X(3) =	0	X(4) =	0
X(5) =	0	X(6) =	0	X(7) =	0	X(8) =	0
X(10) =	5217.60000	X(11) =	1720.00000	X(12) =	3875.00000	X(13) =	0
X(14) =	INDEFINITE	X(15) =	INDEFINITE	X(16) =	INDEFINITE	X(17) =	INDEFINITE
X(18) =	INDEFINITE	X(19) =	INDEFINITE	X(20) =	INDEFINITE	X(21) =	INDEFINITE
X(23) =	20.0400000	X(24) =	3.10000000	X(25) =	43.2000000	X(26) =	0
X(27) =	INDEFINITE	X(28) =	1000.00000	X(29) =	1000.00000	X(30) =	1000.00000
X(98) =	0	X(99) =	1000.00000				

MAIN PROGRAM

```
25          (10+99).F=CLIP((.6*X(10)+X(4)+.425*X(3))/DT+.1*X(10)/DT+25,+AGE)
```

PARAMETER VALUES

FEFT(2) =	.140000000	FEFT(3) =	.700000000E-01	FEFT(4) =	.500000000E-01	FEFT(1) =	.700000000E-01
FEFT(6) =	.200000000E-01	FEFT(7) =	.100000000E-01	FEFT(8) =	0	FEFT(5) =	.300000000E-01
FEFT(10) =	0	FEFT(11) =	0	FEFT(12) =	0	FEFT(9) =	0
FEFT(14) =	0	FEFT(15) =	0	FLFT(1) =	2.00000000	FEFT(13) =	0
FLFT(3) =	1.80000000	FLFT(4) =	1.50000000	FLFT(5) =	1.50000000	FLFT(2) =	2.00000000
FLFT(7) =	.800000000	FLFT(8) =	.600000000	FLFT(9) =	.100000000	FLFT(6) =	1.00000000
FLFT(11) =	.100000000	FLFT(12) =	.100000000	FLFT(13) =	.100000000	FLFT(10) =	.100000000
FLFT(15) =	.100000000					FLFT(14) =	.100000000

SUBROUTINE CYCL1

```
      IF(TIME.EQ.70.)1,2
    1 TSLH=70.
      X(24)=X(24)+.25*X(21)
      X(25)=.75*X(21)+X(25)
   80 X(11)=X(11)+.25*X(8)
      X(12)=X(12)+.75*X(8)
      X(10)=X(10)+X(1)+X(2)+X(3)+X(4)+X(5)+X(6)
      X(23)=X(23)+X(14)+X(15)+X(16)+X(17)+X(18)+X(19)
      X(1)=1.
   85 TPH=0.
      X(14)=X(15)=X(16)=X(17)=X(18)=X(19)=       X(21)=0.
      X(20)=0.
      X(2)=X(3)=X(4)=X(5)=X(6)=X(7)=X(8)       =0.
    2 IF(TIME.EQ.140.)4,3
   90 4 TSLH=140.
      X(11)=X(11)+.25*X(8)
      X(12)=X(12)+.75*X(8)
      X(24)=X(24)+.25*X(21)
      X(10)=X(10)+X(1)+X(2)+X(3)+X(4)+X(5)+X(6)
   95 X(23)=X(23)+X(14)+X(15)+X(16)+X(17)+X(18)+X(19)
      X(25)=.75*X(21)+X(25)
      X(1)=1.
      X(14)=X(15)=X(16)=X(17)=X(18)=X(19)=       X(21)=0.
      X(20)=0.
  100 TPH=0.
      X(2)=X(3)=X(4)=X(5)=X(6)=X(7)=X(8)       =0.
```

E. 3 Initial conditions and updates of the clearcut, rake and burn slash treatment.

STATE VARIABLES - INITIAL VALUES

X(1) =	1.00000000	X(2) =	0	X(3) =	0	X(4) =	0
X(5) =	0	X(6) =	0	X(7) =	0	X(8) =	0
X(10) =	2769.40000	X(11) =	1720.00000	X(12) =	3875.00000	X(13) =	0
X(14) =	INDEFINITE	X(15) =	INDEFINITE	X(16) =	INDEFINITE	X(17) =	INDEFINITE
X(18) =	INDEFINITE	X(19) =	INDEFINITE	X(20) =	INDEFINITE	X(21) =	INDEFINITE
X(23) =	INDEFINITE	X(24) =	3.10000000	X(25) =	43.2000000	X(26) =	0
X(27) =	INDEFINITE	X(28) =	1000.00000	X(29) =	1000.00000	X(30) =	1000.00000
X(98) =	0	X(99) =	1000.00000				

MAIN PROGRAM

```
25          (10,99),F=CLIP((.6*X(10)+X(4)+.425*X(3))/DT,.1*X(10)/DT,25.,AGE)
```

PARAMETER VALUES

FEFT(2) =	.300000000	FEFT(3) =	.150000000	FEFT(4) =	.100000000	FEFT(1) =	.150000000
FEFT(6) =	.800000000E-01	FEFT(7) =	.200000000E-01	FEFT(8) =	0	FEFT(5) =	.800000000E-01
FEFT(10) =	0	FEFT(11) =	0	FEFT(12) =	0	FEFT(9) =	0
FEFT(14) =	0	FEFT(15) =	0	FLFT(1) =	.200000000	FEFT(13) =	0
FLFT(3) =	.180000000	FLFT(4) =	.150000000	FLFT(5) =	.150000000	FLFT(2) =	.200000000
FLFT(7) =	.600000000E-01	FLFT(8) =	.600000000E-01	FLFT(9) =	.600000000E-01	FLFT(6) =	.100000000
FLFT(11) =	.600000000E-01	FLFT(12) =	.600000000E-01	FLFT(13) =	.600000000E-01	FLFT(10) =	.600000000E-01
FLFT(15) =	.600000000E-01					FLFT(14) =	.600000000E-01

SUBROUTINE CYCL1

```
      IF(TIME.EQ.70.)1,2
    1 TSLM=70.
      X(24)=X(24)+.25*X(21)
      X(25)=.75*X(21)+X(25)
      X(11)=X(11)+.25*X(8)
      X(12)=X(12)+.75*X(8)
      X(1)=1.
      TPM=0.
      X(14)=X(15)=X(16)=X(17)=X(18)=X(19)=          X(21)=0.
      X(20)=0.
      X(2)=X(3)=X(4)=X(5)=X(6)=X(7)=X(8)           =0.
    2 IF(TIME.EQ.140.)4,3
    4 TSLM=140.
      X(11)=X(11)+.25*X(8)
      X(12)=X(12)+.75*X(8)
      X(24)=X(24)+.25*X(21)
      X(25)=.75*X(21)+X(25)
      X(1)=1.
      X(14)=X(15)=X(16)=X(17)=X(18)=X(19)=          X(21)=0.
      X(20)=0.
      TPM=0.
      X(2)=X(3)=X(4)=X(5)=X(6)=X(7)=X(8)           =0.
```

APPENDIX F

Appendix F

List of constant names, definitions, and their units.

Parameter Name	Definition	Units
FKIN	Fraction of K in the needles	Dimensionless
FKICT	Fraction of K in the cones and twigs	Dimensionless
FKIR	Fraction of K in the roots	Dimensionless
FKIL	Fraction of K in the litter	Dimensionless
FKIB	Fraction of K in the trunks	Dimensionless
EFK	Exponent for the effect of potassium	Dimensionless
FNGFT	Needle growth function table	Decimal fraction
FCGFT	Cone growth function table	Decimal fraction
FTGFT	Twig growth function table	Decimal fraction
FBGFT	Trunk growth function table	Decimal fraction
FRGFT	Root growth function table	Decimal fraction
TPB	Total plant biomass	$g\ m^{-2}$
AGE	Forest age	Years
TSLH	Time since last harvest	Years
CLR	Cone loss rate	Decimal fraction
TLR	Twig loss rate	Decimal fraction
SLR	Trunk loss rate	Decimal fraction
RLR	Root loss rate	Decimal fraction
RLA1	Rate of OM movement from litter to A1	Decimal fraction
RA1A2	Rate of OM movement from A1 to A2-B2	Decimal fraction
TEMP	Amount of available photosynthate	$g\ m^{-2}\ y^{-1}$
TEMPN	Amount of photosynthate allocated needles	$g\ m^{-2}\ y^{-1}$
TEMPC	Amount of photosynthate allocated cones	$g\ m^{-2}\ y^{-1}$

Parameter Name	Definition	Units
TEMPT	Amount of photosynthate allocated twigs	$g\ m^{-2}\ y^{-1}$
TEMPB	Amount of photosynthate allocated trunks	$g\ m^{-2}\ y^{-1}$
TEMPR	Amount of photosynthate allocated roots	$g\ m^{-2}\ y^{-1}$
TEMP27	Total amount of K in mineral soil	$g\ m^{-2}$
FEFT	K loss due to erosion table	$g\ m^{-2}\ y^{-1}$
FEOFT	OM loss due to erosion table	$g\ m^{-2}\ y^{-1}$
FEOFT	K loss due to leaching table	$g\ m^{-2}\ y^{-1}$
ERODE	Amount of K lost via erosion	$g\ m^{-2}\ y^{-1}$
ERODO	Amount of OM lost via erosion	$g\ m^{-2}\ y^{-1}$
LEACH	Amount of K lost via leaching	$g\ m^{-2}\ y^{-1}$
TOTK	Total amount of K in system	$g\ m^{-2}$
TOTN	Total amount of needles	$g\ m^{-2}$