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Development and application of an upland boreal forest succession model

Daryl Lee Moorhead

Recommended Citation

Moorhead, Daryl Lee, "Development and application of an upland boreal forest succession model. " PhD diss., University of Tennessee, 1985.
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To the Graduate Council:

I am submitting herewith a dissertation written by Daryl Lee Moorhead entitled "Development and application of an upland boreal forest succession model." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Ecology.

Herman H. Shugart, Major Professor

We have read this dissertation and recommend its acceptance:

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

I am submitting herewith a dissertation written by Daryl Lee Moorhead entitled "Development and Application of an Upland Boreal Forest Succession Model." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Ecology.

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We have read this dissertation
and recommend its acceptance:

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The Graduate School

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DEVELOPMENT AND APPLICATION OF AN UPLAND BOREAL FOREST SUCCESSION MODEL

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Daryl Lee Moorhead
March 1985

DEDICATION

I would like to dedicate this work to my wife and family, who provided needed support and understanding.

ACKNOWLEDGMENTS

I would like to thank Dr. K. Van Cleve, Dr. C. C. Amundsen and Dr. D. A. Lietzke for editing, technical advice and encouragement; Dr. L. A. Viereck, Dr. C. T. Dyrness, Ms. J. M. Foote and others at the Institute of Northern Forestry for providing data and technical advice; Ms. M. L. Tharp for invaluable assistance with all aspects of computer modeling; Mr. J. Saldarriaga for many stimulating discussions and suggestions; and, especially, Dr. D. C. West for tremendous expenditures of time and effort on all aspects of this project.

Research sponsored by the National Science Foundation's Ecosystem Studies Program under Interagency Agreement BSR-8315185 with the U.S. Department of Energy under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

ABSTRACT

A mathematical model was developed to simulate forest succession on permafrost and permafrost-free sites for upland sites near Fairbanks, Alaska. Monthly precipitation and ambient air temperature were generated based on long term records. Site-specific incident sunlight was calculated for given aspects and slopes. Soil moisture regimes were estimated monthly based on precipitation and evapotranspiration. Soil thermal regimes were calculated according to available sunlight and net freezing or thawing ambient air temperatures through time. Individual tree growth was estimated annually for all individuals on a plot, modified according to species-specific growth attributes, competitive factors and climatic characteristics. The model successfully simulated the successional patterns of species dominance on both permafrost and non-permafrost sites. Results indicated that species composition and successional dominance on permafrost sites were greatly influenced by species' sensitivities to active layer depth.

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CHAPTER 1

BACKGROUND AND OBJECTIVES

INTRODUCTION

Interior Alaska has 106 million acres of forests with about 22.5 million commercially productive (Hutchinson and Schumann 1976). These boreal forests have been lightly harvested for local use in the past but increasing global demands for wood and fiber may increase pressure on these forests (Viereck 1975). Relative to most of the contiguous United States forests, there is a general lack of base-line data on the Alaskan forests (Hagenstein 1977) although recent efforts by a number of researchers have increased the available knowledge of regeneration, growth and production. Such information is necessary for formulating wise management procedures, devising effective reclamation plans for disturbed areas, and/or providing a basic understanding of the forest community structure and dynamics.

The objective of this dissertation is to present a forest succession model which uses available data to simulate forest development in relation to physical environmental controls for the interior Alaska upland boreal forest.

BACKGROUND

Boreal Forest Characteristics

The upland forests of interior Alaska are typically dominated by fire and contain few tree species (Viereck 1975). Most stands result from secondary succession following wildfire and stands older than

150-200 years are rare due to fire frequencies (Van Cleve and Viereck 1981). Therefore, relatively even-aged mono-specific stands are fairly common.

The climax vegetation on cool, moist, low productive sites is a black spruce (*Picea mariana*) and moss (*Pleurozium* spp. or *Sphagnum* spp.) association. White spruce (*P. glauca*), birch (*Betula papyrifera*), aspen (*Populus tremuloides*) or some mixture of these species may be found where conditions are warmer, drier and more productive (Van Cleve and Sprague 1971, Larsen 1980, Van Cleve et al. 1981).

Site characteristics seem to be of primary importance in determining stand composition. Cooler sites, where permafrost (permanently frozen ground) exists, support low productive black spruce forests with slow nutrient cycling. The warmer areas generally have much more rapid nutrient cycling as well as more productive stands of white spruce or mixed white spruce and hardwoods. Soil temperature may be the single most important factor controlling species dominance (Piene and Van Cleve 1978, Van Cleve et al. 1981).

Fairbanks, Alaska, the locale of the present study, lies in the discontinuous permafrost zone of interior Alaska. Permafrost occurs on most upland sites underlain by loess soils, except south-facing slopes, and is often maintained due to shading and ground insulation by existing vegetation and forest floor material. It provides a seal limiting water and nutrient loss through ground water drainage and lowers soil temperature, inhibiting litter decomposition (Van Cleve and Dyrness 1978, 1979, Grigal 1979).

Nutrient availability (especially nitrogen) is generally low. Litter decomposition is very slow on cooler sites and large accumulations of organic debris occur. This insulates the ground, compounding lower temperatures, slower decomposition and accentuating litter accumulation. On such sites, nutrient cycling may be extremely slow. Mosses form a nearly continuous ground cover in black and white spruce forests and may be important competitors for nutrients in cooler areas, further limiting tree growth (Van Cleve and Dyrness 1978, 1979).

Different patterns of succession may occur after a fire but all are fairly predictable. Fire intensity and prior community structure usually determine succession pattern. None of the tree species are fire tolerant, so even a fire of moderate intensity will kill standing trees. Most species will sprout to some extent but birch and aspen are especially prolific. Black spruce has semi-serotinous cones, providing an immediate seed source after a burn (Viereck et al. 1979). An extremely intense fire may destroy root stocks and seeds, thus retarding forest reestablishment. However, the tree species produce fairly large quantities of seeds which disperse readily, assuring adequate seed sources from nearby areas.

On colder sites, black spruce generally replaces itself after fire although birch or aspen may temporarily intervene. On warmer sites, white spruce, paper birch and aspen predominate either in pure or mixed stands. White spruce seems to be the climax species and may directly replace itself or slowly dominate stands of birch and/or aspen (Van Cleve and Dyrness 1978, 1979, Van Cleve and Viereck 1981).

Mosses proliferate as stands develop and usually produce a continuous thick mat beneath both spruce types. Succession in stands older than 150-200 years has not been studied since fire frequency limits stand age beyond this point. Since white spruce does not regenerate well on moss-covered soils, it has been suggested that black spruce might eventually dominate if fire was controlled (Wilde and Krause 1960). Some recent observations on very old flood plain stands indicate that white spruce may be eliminated when soil shading and insulation lowers soil temperatures to the point where permafrost develops. In these cases, black spruce may become established (Viereck 1970).

Site conditions deteriorate in mature black spruce stands. Decreasing soil temperatures further limit nutrient cycling and decrease the active layer depth. Shallow permafrost eliminates soil water throughflow, resulting in much wetter surface conditions. Tree productivity decreases and sphagnum moss proliferates (Van Cleve et al. 1981). The hypothetical endpoint of black spruce forest succession may be a treeless moss/lichen community (Strang 1973) if fire is excluded.

The upland forests near Fairbanks, Alaska, have been under intensive examination for several years by researchers at the University of Alaska and the USDA Forest Service Institute of Northern Forestry. Correspondence with personnel at both institutions indicated that the information necessary for constructing an upland boreal forest succession model was available. Subsequent visits provided much of the data required for this work.

The approach used in this study was to modify the FORET model parameters to fit tree characteristics of the Fairbanks area. Additional subroutines were created to simulate important environmental factors, such as incident sunlight, ambient temperature and active layer depth.

Modeling Forest Succession

Data necessary for constructing a forest succession model are frequently hard to obtain. Individual trees have potential lifespans greater than the average researcher. Therefore, age dependent species-specific information is usually obtained from time series observations on individuals (often by successive investigators) or extrapolations based on data collected from different aged trees at a specific point in time. Both sources have limitations but either may provide the essential information (Shugart and West 1980).

Community level dynamics may often be difficult to assess or even observe. In some cases, important competitive factors may be too subtle to detect other than by their results. In other cases, important community level events, such as "conflagration class" wildfires in Douglas fir stands, may not occur within the individual tree's lifetime. In this case, historic records must be used.

Gap models seem particularly well suited for simulating succession, with a minimum amount of detailed information, in naturally regenerating forests. In general, they simulate succession based on individual tree responses to external conditions as determined by species' characteristics. Competitive interactions are estimated in a defined area (the gap).

A remarkably successful approach to gap-modeling was initiated with the JABOWA model (Botkin et al. 1972) and later modified in the FORET model (Shugart and West 1977). This approach accounts for diameter increases in each tree on the given plot every year. Competition is based on shading, determined by relative tree heights and leaf areas (estimated on the basis of tree diameter). The major assumption is that a dominant tree (based on height) produces uniform shading over the entire plot thereby exerting equal suppression of subordinates.

This approach has been successful in simulating succession in a variety of forest types around the world, requiring only modification of specific community level factors (such as fire frequencies) and species' characteristics (Table 1.1).

OBJECTIVES

The primary objectives of this dissertation project are:

1. to construct a computer model which accurately simulates upland boreal forest succession on a loess site, and
2. use it to assess the importance of site aspect and slope effects on forest succession patterns.

DISSERTATION ORGANIZATION

This dissertation is organized into chapters that describe the individual programs and composite model in a stepwise manner. Each chapter contains an introduction to a specific problem, the rationale

Table 1.1. Similar gap models for a variety of forests.

Model	Forest Type	Location	Reference
JABOWA	Hardwood	New Hampshire United States	Botkin et al. 1972
FORET	Hardwood	Tennessee United States	Shugart and West 1977
FORICO	Montane Rain Forest	Puerto Rico	Doyle et al. 1980
BRIND	Montane Eucalyptus	Australia	Shugart and Noble 1981
KIAMBRAM	Subtropical Rain Forest	Australia	Shugart et al. 1980

supporting a modeling approach, the methods used and the results of the analysis. References cited are included at the end of each chapter.

CHAPTER 2

FREEZING, THAWING AND GROWING DEGREE DAYS

INTRODUCTION

The purpose of this chapter is to describe a computer code developed for estimating ambient air freezing, thawing and growing degree day values for the Fairbanks area. These values are used to estimate freezing and thawing in soils and to modify species' growth rates in the FORET model.

RATIONALE

Growing degree days are calculated by generating a sine curve of daily ambient temperatures through the year (period = one year, amplitude = difference between mean July and January temperatures). Daily temperatures above the threshold value of 5 degrees Centigrade are summed. Since long-term temperature records for the Fairbanks area are available (NOAA 1977), generated values could be compared to actual observations.

METHODS

A sine function of temperature through time was used to generate daily temperature estimates as described. Monthly estimates of freezing, thawing and growing degree days were obtained in this manner by modifying the threshold value and recording monthly sums. Montnly values of growing degree days were added to yield an annual total. To provide an evaluation of the sine function estimates, a second approach subtracted the recorded monthly mean temperatures from the threshold values and multiplied these differences by the number of days in each month. An additional comparison to sine curve estimates was made by assuming that daily temperatures followed linear interpolations between mid-month temperature means. These estimated daily temperatures were then used to calculate the degree day values.

RESULTS

The results of the three methods indicated a phase shift between sine function estimates and recorded values, possibly representing the influence of local thermal inertia (Fig. 2.1). Mean monthly temperatures for 1982 were similar to 40 year monthly means for the area (NOAA 1977). The sine function produced lower melting degree day estimates and greater freezing values (Table 2.1). The total yearly freezing degree day estimate from the sine function was almost 6% greater than that obtained with the interpolative method and the total annual thawing degree day value was about 8% lower.

CONCLUSIONS

All methods produced similar results but the phase shift in the sine function output could be important considering the interactions of seasonal soil moisture and temperature patterns. For this reason, the method using daily temperature values estimated by interpolation between monthly means was selected.

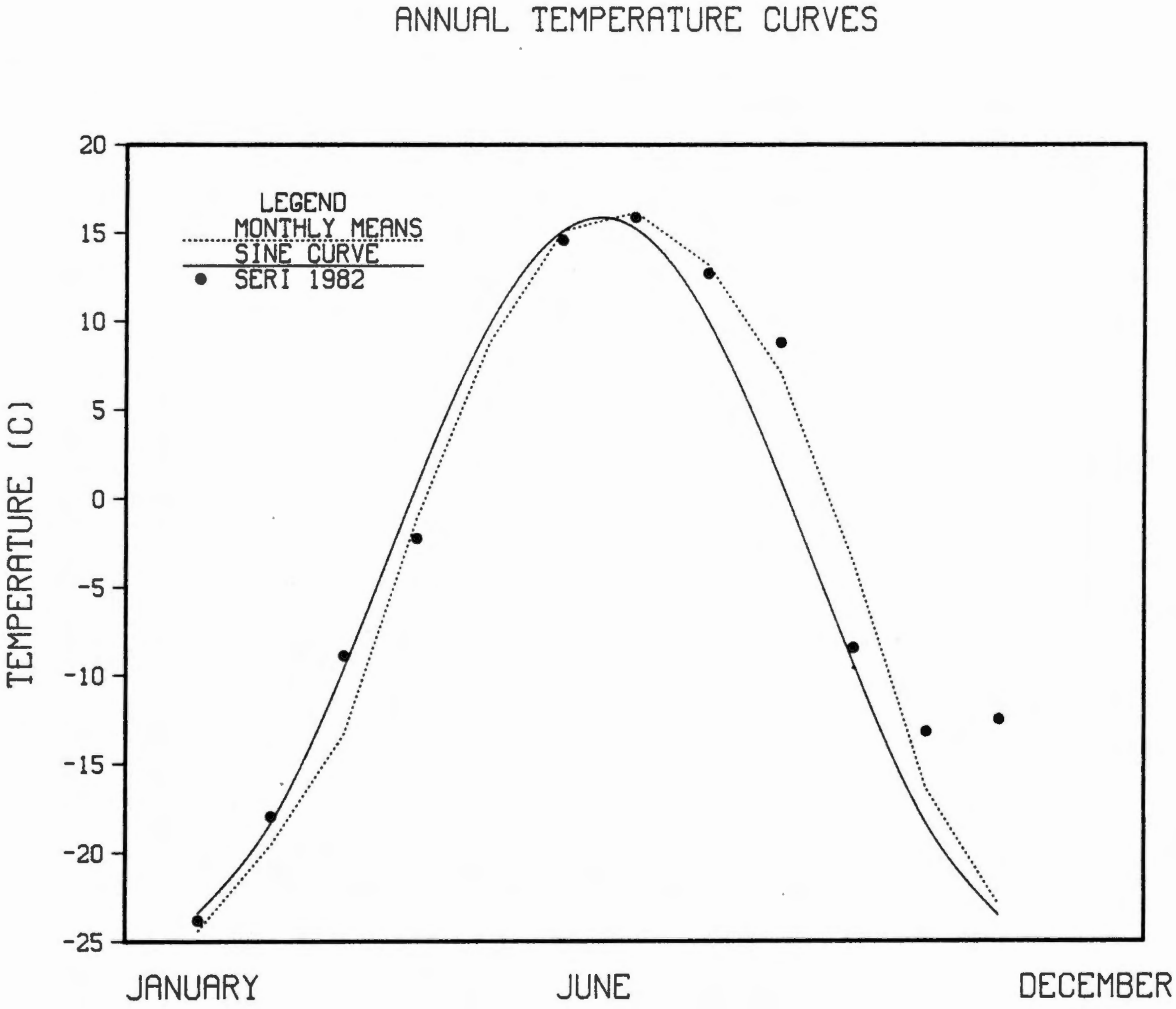

Figure 2.1. Annual ambient air temperature curves for Fairbanks, Alaska. Monthly mean values from NOAA (1977).

Table 2.1. Estimated degree day values for the Fairbanks area, Sine = sine function output, Mean = monthly mean estimates, Day = daily temperature interpolations.

	Sine		Mean		Day	
Month	Freeze	Thaw	Freeze	Thaw	Freeze	Thaw
1	725.60	0.0	756.40	0.0	730.76	0.0
2	514.11	0.0	547.68	0.0	541.13	0.0
3	299.92	0.0	413.85	0.0	389.81	0.0
4	27.99	49.39	33.90	0.0	61.19	22.88
5	0.0	303.33	0.0	272.18	0.0	259.22
6	0.0	453.63	0.0	453.90	0.0	435.70
7	0.0	472.46	0.0	501.27	0.0	485.71
8	0.0	310.95	0.0	408.89	0.0	395.90
9	23.74	55.17	0.0	211.80	0.0	191.99
10	289.61	0.0	111.60	0.0	125.97	4.35
11	550.21	0.0	492.60	0.0	473.01	0.0
12	706.65	0.0	688.50	0.0	671.99	0.0
Totals						
Freezing		3159.57		3044.53		2993.84
Thawing		1644.92		1848.13		1795.74

CHAPTER 3

INCIDENT SUNLIGHT

INTRODUCTION

Programs are available for calculating sunlight energy incident to surfaces of various orientations (Gloyne 1965, Weiss and Lof 1980). The most complex of these calculate insolation based on latitude and characteristics of light transmission through the atmosphere (Liu and Jordan 1960, Klein 1977, Temps and Coulson 1977). Unfortunately, most models require detailed meterological information, not generally available, which limits their practical applications. A much simpler approach is to compute an "equivalent latitude" on the basis of aspect, slope and elevation for the given site and transform the sunlight input accordingly (Trimble and Weitzman 1956, Lee 1962, Lee and Baumgartner 1966, Swift and Knoerr 1973, Dingman and Koutz 1974, Stage 1976, Roise and Betters 1981). This approach is popular in forest studies but is limited to daily mean insolation adjustments. Most of the dynamics of diurnal and seasonal fluctuations in light characteristics are lost. Therefore, a more empirical approach is needed which captures the important dynamics of solar radiation and is still simple enough for general application.

The goal of this chapter is to describe the mathematical model used to calculate the input of light energy to the surface of a given plot. Energy values will be in units of $(\mathrm{cal})(\mathrm{cm}^{-2})(\mathrm{day}^{-1})$ for direct use in soil thermal calculations (unless otherwise specified).

RATIONALE

Estimating site-specific incident solar radiation requires the addition of direct and diffuse components. Since summaries of monthly global radiation are available (Lof et al. 1966) and methods of calculating direct and diffuse components exist (Iqbal 1980, Lowry 1980, Hatfield et al. 1981, Peterson and Dirmhirn 1981, Erbs et al. 1982), a general approach based on this information was determined most appropriate.

Diffuse light intensity is not completely independent of either the sun's position or cloud patterns (Blackburn 1982, Wesley 1982). However, the models which predict diffuse light distributions over the celestial hemisphere require extensive short-time interval information (McArthur and Hay 1981). For the purposes of this work, a simple isotropic distribution of diffuse light was assumed.

Calculating direct beam radiation requires tracking the position of the sun with respect to the plot orientation through time and calculating the appropriate angular corrections. Available radiation records can then be transformed to estimate site-specific insolation.

METHODS

Tracking the position of the sun with respect to a specific site orientation involves diurnal and seasonal cycles. The programs of Barkstrom (1981) and Klein (1977) were used to calculate the seasonal declination of the sun and the daily time-arc described by the sun's path, given the latitude of the site. This provided the necessary yearly and daily parameters for determining the position of the sun throughout the day for a specified location and date. Both programs also estimate total extraterrestrial radiation incident to the surface of the earth's atmosphere at the given latitude.

To develop a model as generally applicable as possible, it was decided to use available sunlight data. This is usually recorded as total radiation incident to a horizontal surface (i.e., global radiation). Therefore, it was necessary to estimate the direct and diffuse components. The techniques of Liu and Jordan (1960) and Page (1961) were used for calculating these values based on extraterrestrial radiation estimates (Klein 1977, Barkstrom 1981) and surface sunlight records (Bryson and Hare 1974, Lof et al. 1966).

Direct and diffuse light adjustments for slope were estimated by finding the ratio of the sun angle to the slope versus the sun angle to the horizontal. This value was then multiplied by the horizontal direct and diffuse sunlight components to produce slope incident values.

Recorded values of global radiation are usually presented as monthly mean day values in energy per unit area, eg., (kj)(m^{-2})(day^{-1}) or (cal)(cm^{-2})(day^{-1}) (units will be specified throughout this chapter). It is necessary to estimate the hourly (or other time unit) light input in order to transform values for slopes. Therefore, it was assumed that light intensity described a sine curve over the day and that integrating this curve would produce the daily recorded total incident light. This permitted the estimation of site-specific time-dependent values which could then be summed to yield total light input.

The Geopyhsical Institute at the University of Alaska, Fairbanks, recorded about 17 months of continuous solar energy information from August 1981 through December 1982. These data were obtained from the Solar Energy Research Institute (SERI), Boulder, Colorado, for comparisons to calculated values. Monthly average diurnal sunlight curves were standardized to a maximum amplitude of 1.0 by dividing hourly recorded values by the maximum daily intensities. Diurnal time scales were also standardized by setting the total daily sunlight period equal to 1.0. This permitted comparisons of intensity patterns between months and simplified comparisons of recorded to calculated values.

RESULTS

Extraterrestrial Radiation

The techniques of Barkstrom (1981) and Klein (1977) for estimating extraterrestrial radiation incident to the earth's atmosphere were compared (Table 3.1). The differences were largest at 43 degrees north latitude during September when Barkstrom was about 8% higher and at 65 degrees north latitude during November when Barkstrom was 18% higher. Average differences were 3% at 43 degrees and 7% at 65 degrees. During the principle thawing months of May through September, differences averaged less than 4% at 65 degrees latitude. The Barkstrom model required a great amount of additional coding and calculation but did not produce results much different from the Klein model. Therefore, the simpler Klein equations were used.

Table 3.1. Estimated monthly radiation incident to the earth's atmosphere according to Barkstrom (1981) and Klein (1977) in units of $(\mathrm{kj})(\mathrm{m}^{-2})(\mathrm{day}^{-1})$, Ratio = Barkstrom/Klein.

	43 degrees latitude			65 degrees latitude		
Month	Barkstrom	Klein	Ratio	Barkstrom	Klein	Ratio
1	13119.36	12614.57	1.04	1137.03	1053.47	1.08
2	18875.79	17765.98	1.06	5802.93	5228.63	1.11
3	26363.18	25651.87	1.02	14280.58	13606.57	1.05
4	34433.51	32585.98	1.05	25872.80	24346.34	1.06
5	40594.96	40386.53	1.01	36751.37	36558.29	1.01
6	43382.13	41397.89	1.05	42570.16	40639.02	1.05
7	42202.51	42651.79	0.99	40009.09	40385.58	0.99
8	37276.54	36705.64	1.02	30627.40	29927.45	1.02
9	29891.87	27805.52	1.08	19030.99	17230.13	1.10
10	21711.52	20694.39	1.05	8745.28	7768.89	1.13
11	14908.29	14557.08	1.02	2354.37	1998.81	1.18
12	11733.14	11810.06	0.99	406.70	366.53	1.10

$$\mathrm{DEC} = 23.45(\sin(360(284+\mathrm{DAYS})/365))$$

$$\mathrm{ALT} = \mathrm{asin}(\sin(\mathrm{LAT})\sin(\mathrm{DEC}) + \cos(\mathrm{LAT})\cos(\mathrm{DEC})\cos(\mathrm{HR}))$$

$$\mathrm{AZM} = \mathrm{asin}(-\cos(\mathrm{DEC})\sin(\mathrm{HR})/\cos(\mathrm{ALT}))$$

DEC = Solar declination

DAYS = Average monthly day of the year

LAT = latitude

ALT = Sun altitude

HR = Sun hour angle

AZM = Sun azimuth

Angular values in degrees

Recorded Global Radiation

Two data sets of global radiation for the Fairbanks area were used to calculate the ratios of diffuse to total horizontal radiation (Lof et al. 1966, Bryson and Hare 1974). Differences between Barkstrom and Klein still averaged less than 10%, ratios calculated according to Liu and Jordan (1960) were 10 to 20% less than those estimated by Page (1961), but the biggest variations observed were between global radiation data sets (Tables 3.2 and 3.3). The data set of Lof et al. (1966) was chosen for this study since it is a ten year summary of observed values while Bryson and Hare (1974) present estimations. Page's (1961) equation for calculating the direct and diffuse components of sunlight was selected for its simplicity and greater diffuse light estimates, which seemed more realistic for higher latitudes.

$$\mathrm{RATIO} = 1.00 - 1.13(\mathrm{EXTRA}/\mathrm{GLOBAL})$$

RATIO = Diffuse/direct light components
EXTRA = Extraterrestrial radiation
GLOBAL = Global radiation

SERI Data Set

The SERI data were compared to those of Lof et al. (1966), Bryson and Hare (1974) and Kusuda and Ishii (1977). The latter work estimated sunlight values with a modified Liu and Jordan (1960) model. The results of this comparison showed the SERI data set had consistently lower values of sunlight than the other studies (Table 3.4).

Table 3.2. Ratios of diffuse to total radiation calculated according to Liu and Jordan (1960) and Page (1961), input data from global radiation records of Lof et al. (1966), calculations based on results of Barkstrom (1980) and Klein (1977), Ratio 1 = Liu and Jordan, Ratio 2 = Page.

	Barkstrom		Klein	
Month	Ratio 1	Ratio 2	Ratio 1	Ratio 2
1	0.2155	0.2094	0.1647	0.1467
2	0.3324	0.3803	0.2872	0.3123
3	0.2293	0.2280	0.2005	0.1898
4	0.2764	0.2960	0.2463	0.2518
5	0.3362	0.3859	0.3340	0.3827
6	0.3559	0.4143	0.3366	0.3865
7	0.4012	0.4749	0.4051	0.4798
8	0.3739	0.4392	0.3643	0.4261
9	0.4600	0.5426	0.4174	0.4947
10	0.4526	0.5347	0.4023	0.4763
11	0.3875	0.4574	0.3194	0.3609
12	0.2804	0.3020	0.2275	0.2255

Table 3.3. Ratios of diffuse to total radiation calculated according to Liu and Jordan (1960) and Page (1961), input data from global radiation records of Bryson and Hare (1974), calculations based on results of Barkstrom (1980) and Klein (1977), Ratio 1 = Liu and Jordan, Ratio 2 = Page.

	Barkstrom		Klein	
Month	Ratio 1	Ratio 2	Ratio 1	Ratio 2
1	0.5019	0.5839	0.4680	0.5509
2	0.3607	0.4211	0.3171	0.3575
3	0.2708	0.2877	0.2467	0.2524
4	0.3163	0.3563	0.2896	0.3159
5	0.3513	0.4078	0.3491	0.4047
6	0.4025	0.4765	0.3831	0.4516
7	0.4236	0.5021	0.4276	0.5068
8	0.4646	0.5474	0.4546	0.5368
9	0.4353	0.5351	0.4105	0.4865
10	0.4284	0.5077	0.3787	0.4458
11	0.4956	0.5780	0.4243	0.5029
12	0.7682	0.7673	0.7216	0.7412

Table 3.4. Global radiation at Fairbanks, Alaska, according to Lof et al. (1966), Bryson and Hare (1974), Kusuda and Ishii (1977) and SERI (personal communication), units in $(cal)(cm^{-2})(day^{-1})$.

Month	SERI	Kusuda	Lof	Bryson
1	14	26	19	10
2	62	100	76	71
3	176	269	233	215
4	327	440	385	352
5	-	497	477	460
6	465	534	527	471
7	407	443	444	421
8	309	314	363	393
9	166	168	184	187
10	68	72	86	91
11	15	18	27	21
12	4	4	6	2

When the SERI monthly global radiation values were used as input to the model, the SERI data still showed more diffuse and less direct light than was calculated (Table 3.5). This was expected since the equations used were developed for clear sky radiation and Fairbanks averages about 70% cloudiness (NOAA 1977) which increases diffuse/direct light ratios. The summer ratios did seem to be similar enough for practical purposes, so no attempts were made to match the SERI data by modifying the model.

Standardized SERI global light intensities followed a polynomial curve when plotted throughout the day (Fig. 3.1). This pattern was consistent for all months, so the model was modified to produce a

Table 3.5. Comparisons of calculated and recorded values of diffuse and direct sunlight radiation components, units in (cal)(cm^{-2})(day^{-1}), Ratio = diffuse/direct, SERI data from 1982.

	SERI			Page		
Month	Direct	Diffuse	Ratio	Direct	Diffuse	Ratio
1	5.17	9.01	1.74	8.80	5.20	0.59
2	26.78	35.01	1.31	34.78	27.22	0.78
3	96.09	80.32	0.84	107.71	68.29	0.63
4	169.85	157.94	0.93	207.80	119.20	0.57
5	-	-	-	214.38	192.62	0.90
6	238.76	226.30	0.95	251.74	213.26	0.85
7	206.58	200.74	0.97	194.06	212.94	1.10
8	153.72	155.14	1.01	150.95	158.05	1.05
9	58.68	107.55	1.83	75.67	90.33	1.19
10	20.38	47.94	2.35	28.16	39.84	1.41
11	2.73	12.31	4.50	5.33	9.67	1.82
12	0.66	3.28	4.97	2.07	1.93	0.94

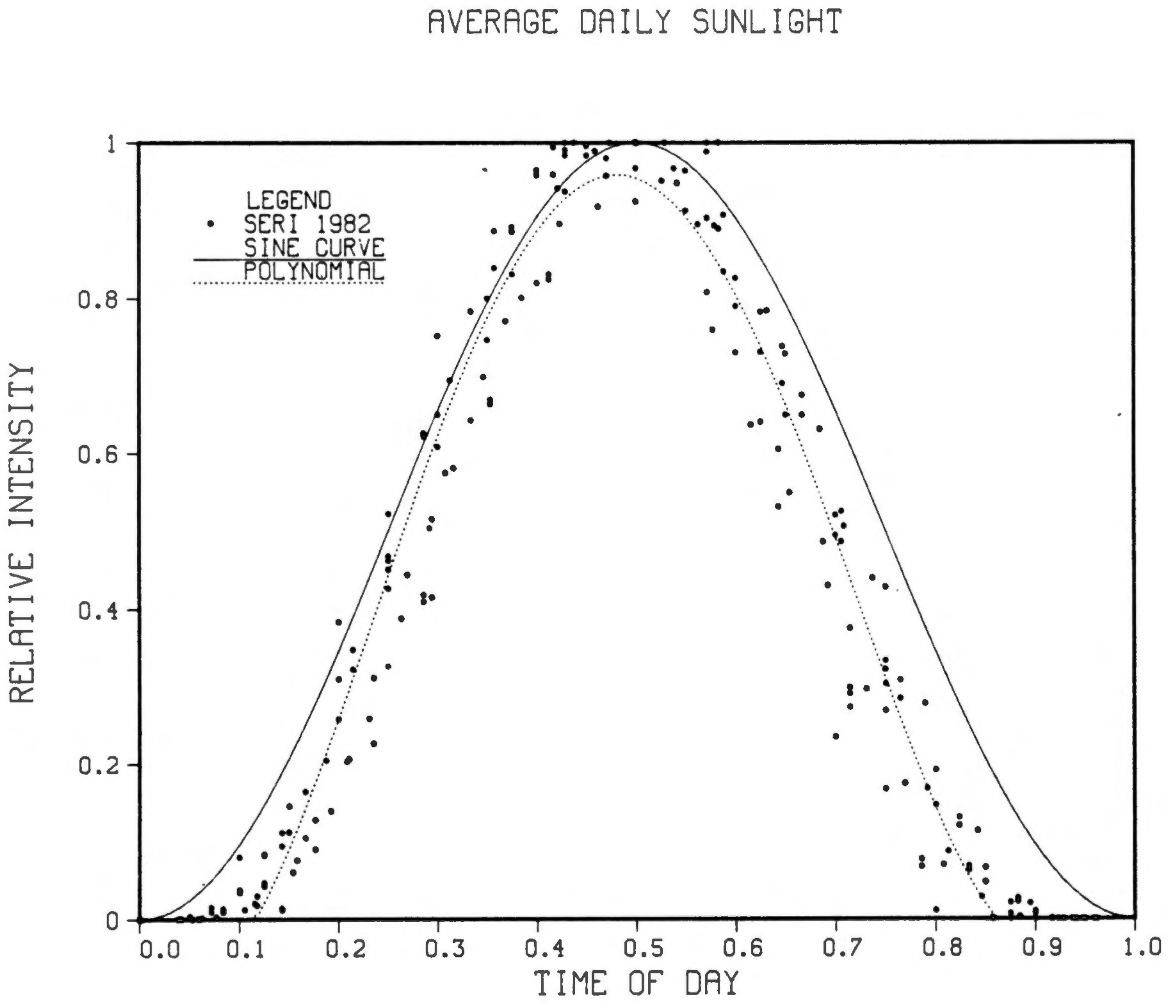

Figure 3.1. Diurnal relative sunlight (scaled 0.0 to 1.0) intensity curves incident to a horizontal surface at 65 degrees north latitude. September global values.

similar diurnal curve (Table 3.6). Computed mean monthly horizontal incident radiation values then closely matched the SERI observations (Table 3.7). The sine curve estimates were consistently 20% larger than the recorded values.

Aspect/Slope Transformation

The SERI data set included total incident sunlight readings for a south-facing sensor inclined to 65 degrees. Hourly slope-incident direct light intensities were obtained by subtracting slope transformed diffuse light readings from these total insolation values. Recorded ratios of direct slope-incident light versus direct horizontal-incident light were compared to calculated values (Table 3.8).

CONCLUSIONS

Observations of incident sunlight for other site orientations were not available for further verifying model output. However, model results seemed realistic for the given conditions. Comparisons of various inclined surfaces (south-facing) showed appropriate patterns in diurnal insolation curves (Fig. 3.2). Additional comparisons of varying aspect (30 degree inclines) also produced expected results (Fig. 3.3). Until additional site-specific insolation data are available, model output will be used for estimating sunlight incidence for all orientations.

Table 3.6. Coefficient estimates for standardized daily light curves, relative light intensity = $a(t) + b(t^2) + c(t^3) + d(t^4)$, relative time of day = t, R-square = 0.9854, relative intensity scaled from 0.0 to 1.0.

Coefficient	Estimate	Std Error	P
a	- 2.9595	0.1640	0.0001
b	32.0533	0.9211	0.0001
c	- 60.4163	1.6126	0.0001
d	31.5692	0.8837	0.0001

Table 3.7. Mean monthly horizontal incident light according to SERI and the model with sine and polynomial functions, units in $(cal)(cm^{-2})(day^{-1})$, Ratio = SERI/Model.

Month	SERI	Sine	Ratio	Polyomial	Ratio
1	14	16.72	0.84	14.21	1.01
2	62	77.93	0.80	61.62	1.00
3	176	218.99	0.80	175.87	0.99
4	327	413.36	0.79	327.35	1.00
5	[407]	516.81	0.79	406.83	1.00
6	465	589.83	0.79	464.69	0.99
7	407	513.34	0.79	406.95	0.99
8	309	392.16	0.79	308.89	1.00
9	166	209.61	0.79	166.09	1.00
10	68	84.03	0.81	68.22	1.00
11	15	16.61	0.90	14.69	1.02
12	4	3.88	1.03	3.51	1.14

Table 3.8. June daily direct radiation incident to a south-facing 65 degree slope, units in (cal)(cm^{-2})(day^{-1}), Ratio = slope/horizontal.

Hour	SERI			Model		
	Level	Slope	Ratio	Level	Slope	Ratio
5	2.29	0.32	0.1377	3.84	0	0
6	5.51	0.95	0.1730	8.74	0	0
7	11.60	3.86	0.3325	13.94	4.50	0.3231
8	14.62	10.24	0.7004	18.85	15.77	0.8367
9	19.70	17.75	0.9008	22.99	23.72	1.0321
10	22.37	23.45	1.0481	26.00	29.93	1.1512
11	23.66	27.65	1.1688	27.64	33.61	1.2157
12	22.98	28.32	1.2324	27.79	34.36	1.2362
13	25.99	32.02	1.2321	26.45	32.15	1.2157
14	26.36	30.25	1.1475	23.71	27.30	1.1512
15	16.58	18.84	1.1365	19.82	20.45	1.0321
16	14.50	14.08	0.9714	15.12	12.65	0.8367
17	12.43	9.95	0.8004	10.07	5.26	0.5221
18	9.35	4.63	0.4951	5.25	0	0
19	6.18	1.50	0.2433	1.37	0	0

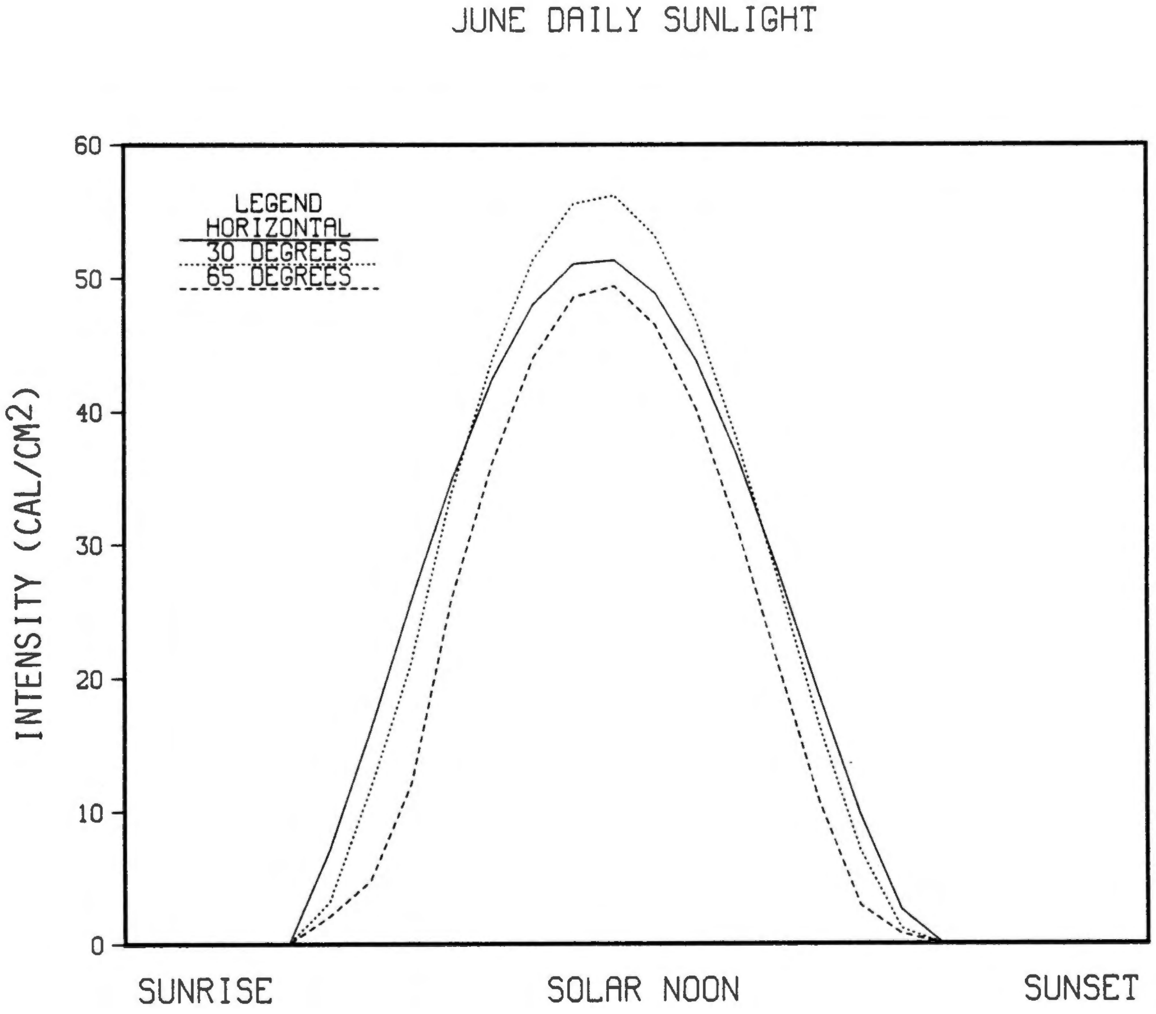

Figure 3.2. Simulated diurnal sunlight pattern incident to three south-facing slopes of varying inclination.

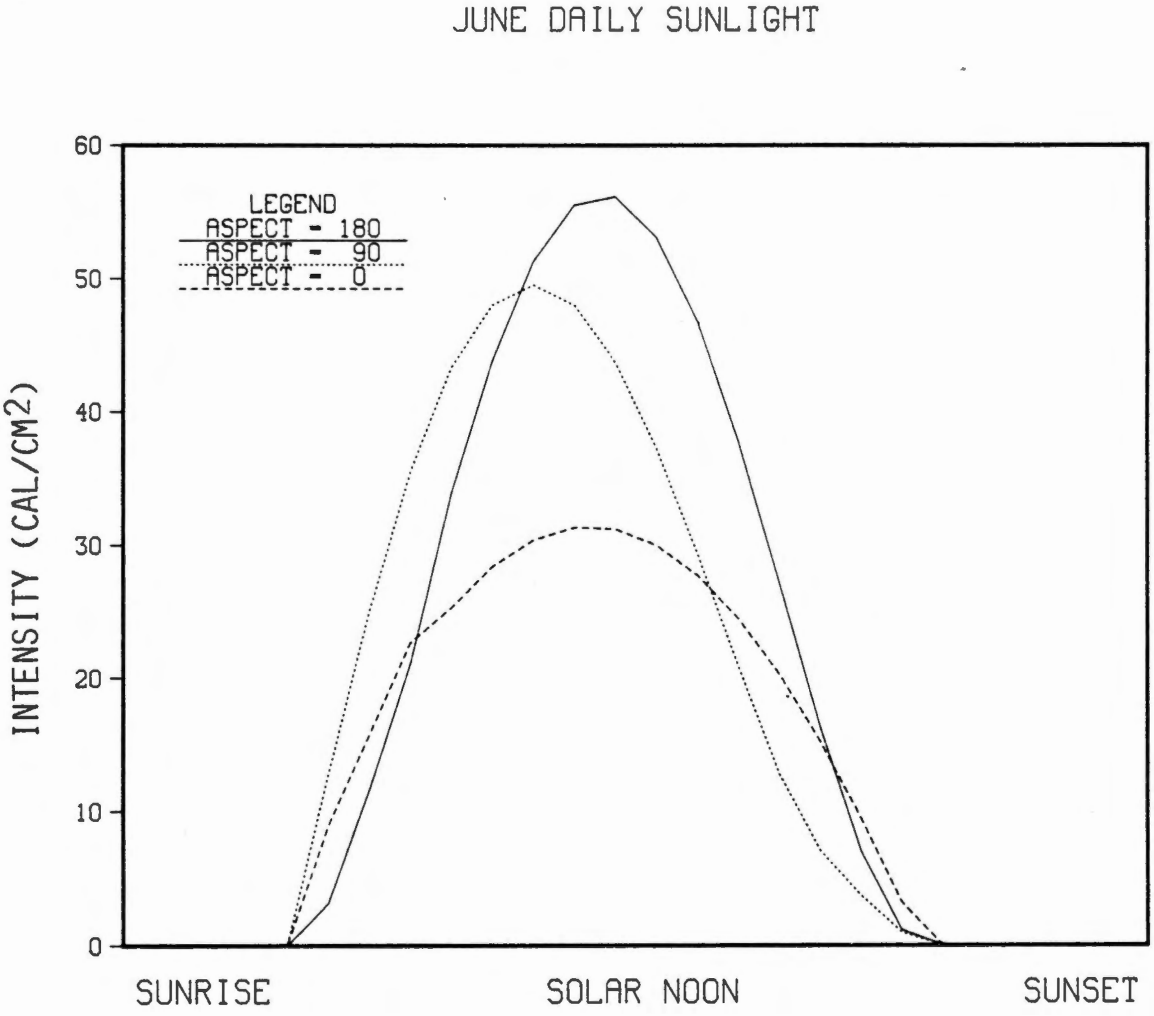

Figure 3.3. Simulated diurnal sunlight pattern incident to three inclined surfaces (30 degree slope) of varying aspect.

CHAPTER 4

SOIL MOISTURE

INTRODUCTION

Soil moisture significantly affects tree growth (Eis 1967, Payandeh 1973, Lowry 1975, Page 1976, Brix 1979). The effects are direct (physiological moisture needs) and indirect (influencing soil temperature regime). Tree response to drought has been well documented (Kozlowski 1976, Kramer and Kozlowski 1979). Information concerning tree response to water saturated or flooded conditions is also available (Kozlowski 1982).

Species differ in their water requirements and tolerances to extreme moisture regimes. The capability of a soil to store and release water throughout the growing season (unfrozen conditions) determines species-specific growth responses on the given site. Soil thermal characteristics are also influenced by water content. Organic layers have low heat conductivities and capacities when dry but the reverse is true when they are moist. The temporal pattern of soil moisture content is a major factor influencing permafrost distribution and total thaw depth (active layer) in subarctic environments. Soil moisture content and phase (ice and/or liquid) throughout the year controls the annual soil thermal regime for a given site.

Species distributions and succession patterns are related to active layer depth in subarctic regions (Dingman and Koutz 1974, Grigal 1979, Van Cleve and Viereck 1981, Foote 1983, Viereck et al. 1983).

Soil moisture regimes must be evaluated in order to determine thermal characteristics of soil layers, permitting assessment of permafrost development and dynamics.

The objective of this chapter is to describe a simulation program which is used to calculate temporal soil moisture patterns in forest soils of the upland Fairbanks region.

RATIONALE

Soil moisture is increased by precipitation and decreased by evapotranspiration and soil throughflow. The upper limit on soil water retention is determined by soil characteristics when topography allows for maximum infiltration. Monthly records of precipitation and temperature are generally available, which permit assessment of moisture input. Evapotranspiration has been estimated on the basis of precipitation, temperature and soil waterholding capacity (e.g., Thornthwaite and Mather 1955, 1957). Soil characteristics are detailed in soil surveys which include estimated moisture holding capacities and permeabilities. Available forest stand inventories include topographic features of slope and aspect which permit the estimation of infiltration and evapotranspiration potentials. Monthly calculations of soil moisture input (precipitation) and output (overland runoff, throughflow and evapotranspiration), limited by soil attributes, provide a continuous approximation of moisture conditions. This information permits evaluating the direct effects of soil water availability on tree growth and calculating soil thermal characteristics.

METHODS

Available Model

A computer model of soil moisture dynamics has been developed (Mann and Post 1980, Solomon et al. 1984a, 1984b). It was originally designed and used in simulations to consider the effect of soil moisture availability on succession patterns in the eastern deciduous forests of North America. Precipitation, temperature, and Thornthwaite evapotranspiration formulae are used to calculate monthly soil moisture content. Evapotranspiration is estimated in the model as follows.

$$\mathrm{TMON} = (0.2\mathrm{TMEAN})^{1.514}$$

$$\mathrm{TE} = \Sigma^{12}\,(\mathrm{TMON})$$

$$A = 4.000001\,(\,0.675(\mathrm{TE}^3) - 77.1(\mathrm{TE}^2) + 17920.0(\mathrm{TE}) + 492390.0)$$

$$U = 1.6(10(\mathrm{TMEAN}/\mathrm{TE}))A)C$$

TMON : Monthly temperature efficiency

T : Mean monthly temperature (°C)

TE : Annual temperature efficiency

A : Exponent of evapotranspiration

C : Monthly daylength correction factor

U : Monthly evapotranspiration (cm water)

This equation overestimates water losses when soil moisture content is below field capacity. Actual evapotranspiration is affected by varying available soil water content. A negative exponential function has been used to relate soil water storage and potential water loss (Pastor and Post 1984). Estimates of each soil layer's loss was estimated in a similar manner by the following negative exponential function.

EVAP = AVAIL(exp(-FIELD/AVAIL))

EVAP : Estimated maximum evapotranspiration
AVAIL : Actual available water
FIELD : Soil field capacity
Moisture values as cm water

For the present study, this model was modified to include additional important moisture characteristics of the upland loess soils in the Fairbanks area, Alaska. These changes include estimations of water saturated conditions and snow cover. The model was also expanded to separately evaluate individual soil layers. Derivation of temporal soil moisture patterns without consideration of thermal regime is simplistic but does provide an approximation of soil moisture conditions through the growing season.

Saturated Conditions

The model (Mann and Post 1980) sets the upper limit of soil water content at field capacity and assumes that all soils are freely drained of excess water. This assumption is not acceptable for the upland soils near Fairbanks. A site-specific wetness category was added to the model. Values between 0 and 1 set upper limits of soil moisture content between saturation and field capacity, respectively.

VALUE = DRAIN(SAT-FC) + FC

VALUE = Maximum water content
DRAIN = Wetness classification (0.0 to 1.0)

SAT = Saturation level

FC = Field capacity

Moisture values as cm water/cm soil

Wetness classification is approximated on the basis of site topography and soil characteristics. Field capacities were taken from the Fairbanks area soil survey (Rieger et al. 1963) and saturation values estimated on the basis of texture and water holding capacity (Lietzke, per. com.).

Snow Cover

Fairbanks has a long cold winter with significant snow accumulation (NOAA 1977). There is little change in the soil water content until snow melts and infiltrates into the soil during spring. The model was modified so that precipitation accumulated during the months with mean temperatures below freezing and was added to the soil when ambient temperatures rose above freezing (assuming no overland runoff). The Stephan formula for frost penetration in a multilayer soil system was used to simulate snow melt (Jumikis 1966).

$$\text{DEGD} = (L(\text{ACCUM}^3))/(48k)$$

DEGD : Degree days to melt snow

L : Latent heat of fusion (80 cal/g)

ACCUM : Accumulated precipitation (cm)

k : Conductivity of water $(\text{cal})(\text{cm}^{-2})(\text{hr}^{-1})(°\text{C}^{-1})$

Monthly melting degree day values were compared to DEGD to determine actual monthly snow melt. Thornthwaite calculations indicate no evapotranspirational losses during freezing weather. Sublimation of accumulated snow probably occurs but there is no apparent agreement on its importance. No attempt was made to estimate this loss.

Soil Layers

The upland mineral soils in the Fairbanks area are relatively uniform between sites, but organic surface layers differ greatly (Van Cleve and Dyrness 1978). Deciduous stands have little organic accumulation and almost no moss. White spruce stands support a relatively continuous moss mat and accumulate a total moss/litter depth of 5-10 cm. Black spruce sites may show moss/litter accumulation depths exceeding 50 cm. The model was expanded to include moss, litter and mineral soil components. Each soil layer was independently assessed for moisture content through time and total soil moisture consisted of the combined values. The major assumption was that the soil profile usually moistened and dried from the surface downward. The surface organic layers were assumed to moisten from the lower layers upward when the moisture level in the layer above exceeded field capacity. Values were updated monthly. Generalized soil layer bulk densities were used in this routine (Table 4.1). These values were similar to those recorded in the literature (Mader 1953, Rieger et al. 1963, Heilman 1968, Thorud and Anderson 1969, Dingman 1971, Loomis 1977, Viereck and Dyrness 1979, Barney et al. 1981). Field capacities were based on values reported in the literature and from field data (Rieger et al. 1963, Dingman 1971).

Table 4.1. Bulk densities and moisture characteristics of boreal forest soil layers, BD: Bulk density (g/cm^3), FC: Field capacity and SAT: Saturation (cm water/cm soil).

Layer	BD	FC	SAT
Moss	0.016-0.116	0.39	0.95
Litter	0.160-0.310	0.11-0.21	0.38-0.70
A	0.410-1.150	0.21-0.37	0.46-0.83
C	1.170-1.390	0.23-0.30	0.35-0.45

RESULTS

Evapotranspiration

Measured summer pan evaporation often exceeds total annual precipitation in the Fairbanks area (Table 4.2). Mean summer evaporation totalled 55.17 cm for the 1970 to 1979 period (Alaska University Experimental Station) while annual precipitation averaged 26.56 cm. Monthly mean recorded temperatures at the Fairbanks International Airport and the Experimental Station (Fairbanks area) for 1980, 1981 and 1982 were used to calculate evapotranspiration without the limitations imposed by actual soil moisture content (Table 4.3). Total evaporation was measured during these summers at the Experimental Station (NOAA 1980, 1981, 1982). Comparisons of estimated to observed values indicated close agreement during June with differences becoming larger as summer progressed.

Soil Moisture Simulations

Two general classes of soil conditions were examined which typify the extremes of the area, i.e., well-drained, southern aspect white spruce and poorly-drained, northern aspect black spruce forests (Table 4.4). Simulation results showed little effect of wetness classification on soil moisture patterns. Any effect which wetness classification might exert would probably be small in comparison to the relatively large estimated evapotranspirational losses. Estimates of evapotranspiration required further modification in order to obtain a reasonable match of simulated forest soil moisture values to reported data. This was achieved when specific soil layer evapotranspiration

Table 4.2. Total observed evaporation and annual precipitation for the Fairbanks area (in cm water), means, standard deviations (Std) and sample sizes (N).

	Evaporation					
Year	May	Jun	Jul	Aug	Sep	Precipitation
1970	13.92	11.35	11.28	7.14	-	38.66
1971	17.32	11.73	6.68	4.11	-	34.57
1972	-	13.33	14.61	7.59	-	23.67
1973	-	12.45	13.00	-	5.66	33.27
1974	-	13.87	12.73	7.85	-	23.72
1975	-	13.11	-	8.71	-	16.31
1976	-	12.55	17.07	10.62	-	19.99
1977	-	16.03	15.04	10.62	-	30.56
1978	-	8.79	-	10.13	-	23.55
1979	-	11.07	10.85	8.97	-	21.31
Mean	16.00	12.43	12.66	8.42	5.66	26.25
Std	1.87	1.92	3.16	2.07	-	7.25
N	2	10	8	9	1	10

Table 4.3. Potential evapotranspiration estimates and observed evaporation for the Fairbanks area (in cm water).

Year	Month	Experimental Station		Air Port
		Observed	Estimated	Estimated
1980	6	11.38	10.93	10.72
	7	11.86	12.27	12.38
	8	6.83	8.93	8.91
1981	6	11.18	10.69	11.62
	7	8.26	10.90	10.88
	8	7.09	9.00	8.99
1982	6	10.97	11.14	11.17
	7	-	12.72	12.91
	8	6.78	9.12	9.68
	9	3.02	5.53	6.08

Table 4.4. Forest floor characteristics for simulating moisture regime in a southern aspect white spruce system and a northern aspect black spruce system.

Layer	Depth	Bulk Density	Field	Saturation
White Spruce				
Litter	10.0	0.100	0.16	0.54
A	10.0	0.645	0.29	0.45
C1	10.0	1.100	0.30	0.45
C2	600.0	1.400	0.23	0.35
Black Spruce Deep Moss				
Moss	10.0	0.060	0.39	0.95
Fiber	10.0	0.100	0.33	0.54
Humus	10.0	0.100	0.30	0.50
C2	600.0	1.400	0.23	0.35

values were further reduced by 70% of the estimated values. Results of 100-year simulations for the white spruce forest soil indicated an increase in moisture values during May, dropping through the summer (Fig. 4.1). The black spruce soil showed a similar pattern, with a much greater fluctuation in surface moss moisture content through the summer (Fig. 4.2).

Model Validation

A data set was available which contained summer monthly moisture content of the litter and upper mineral soil layers in a mature white spruce forest. Recorded monthly total precipitation and mean temperatures for the Fairbanks area were used as input to the moisture routine for three years (NOAA 1980, 1981, 1982) in an attempt to match the soil water content during the summer of 1982. The soil profile used in this simulation consisted of average soil bulk densities for a white spruce forest (Table 4.4). Field capacities of 150% water by dry soil weight for litter and 45% for the A-horizon were used. Predicted values were high for litter moisture content during June, very close to observed values during July and August, and low during September (Table 4.5). Mineral soil values were similar to observed values from July through August but too low in September. The overall trend in predicted values is logically consistent with the temperature, precipitation, estimated evapotranspiration and soil characteristics. Limitations of this test include no indication of lateral water movement or ground ice melt. In addition, actual evapotranspiration may be lower than estimated if the diminishing trend observed in early

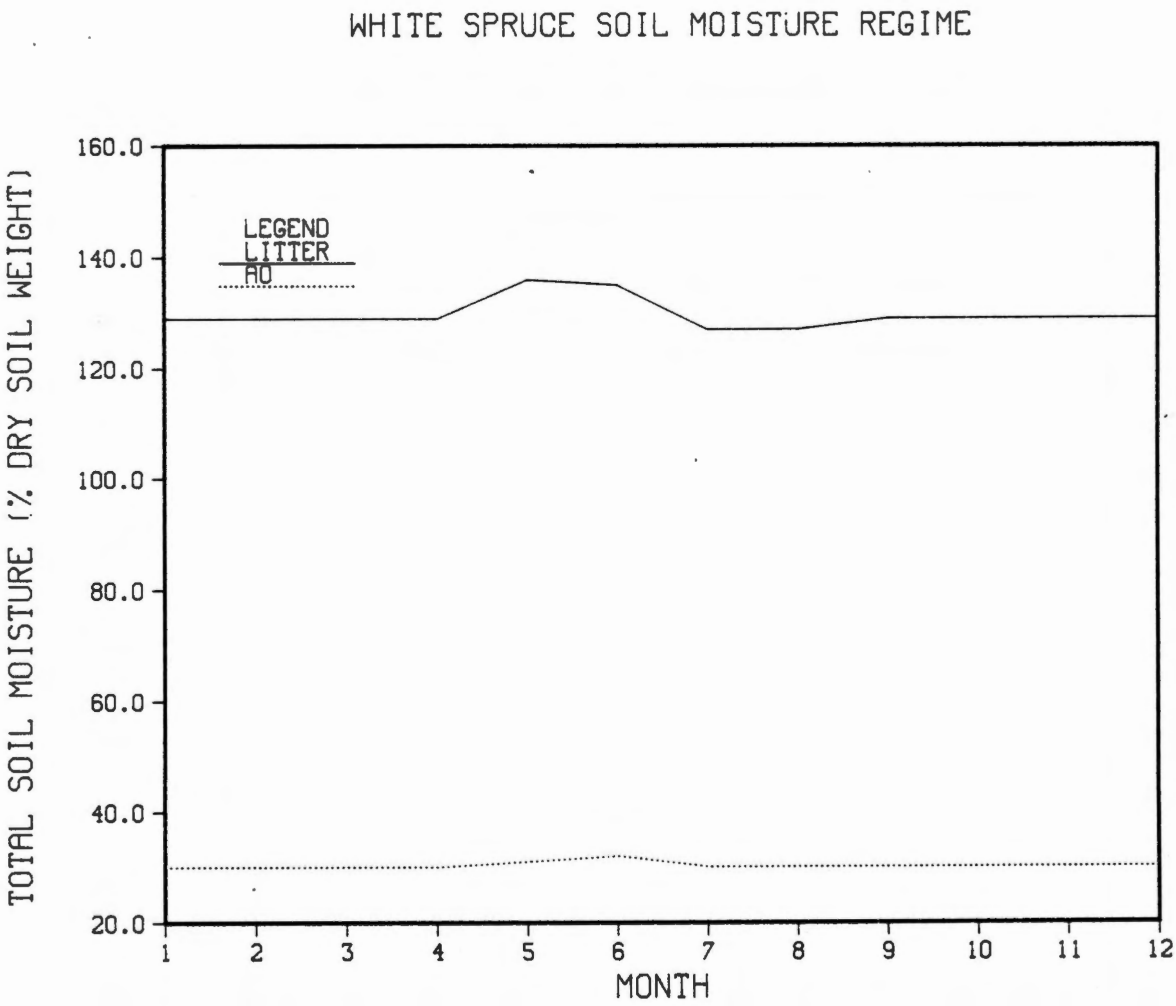

Figure 4.1. Moisture content of litter and surface soil layer in a white spruce forest through time.

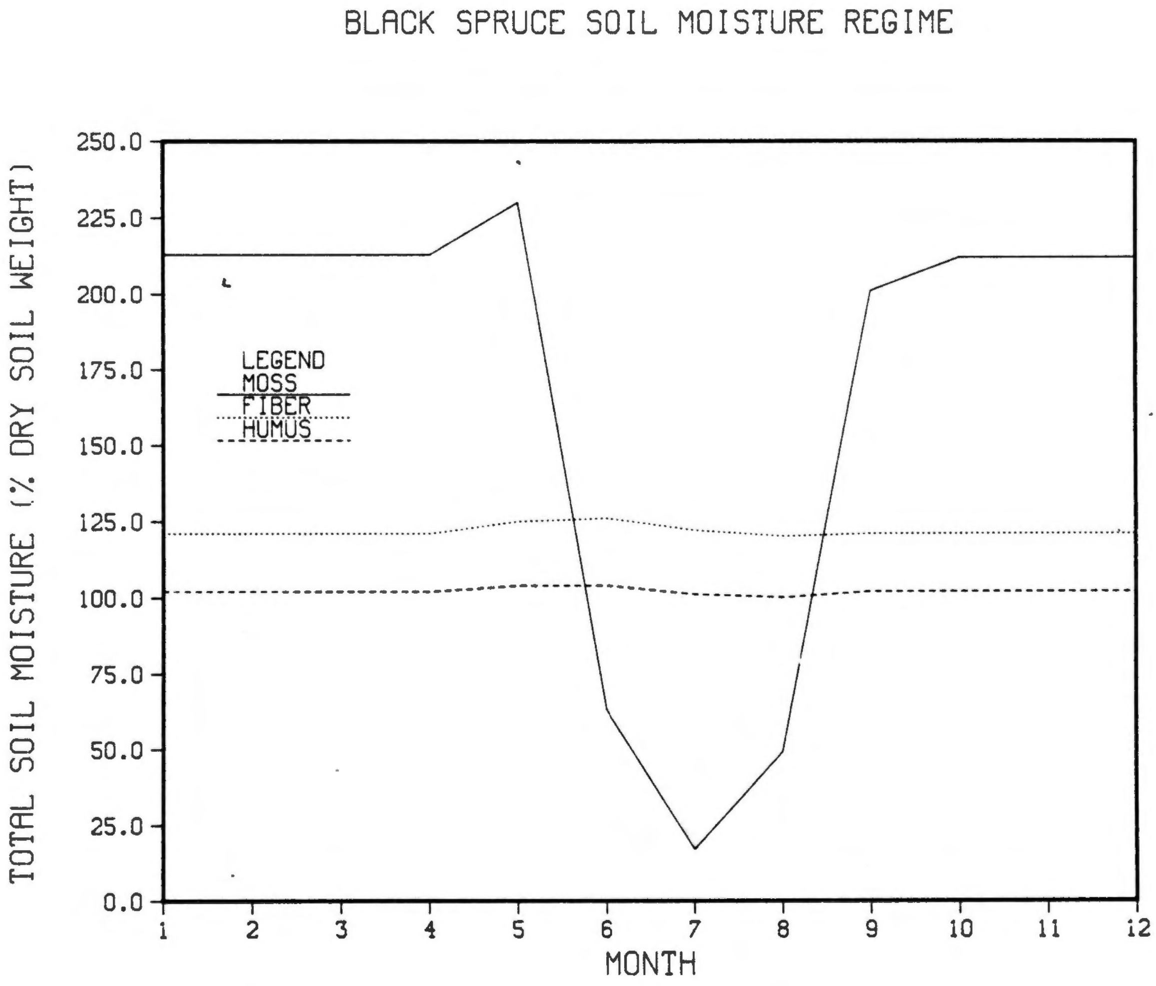

Figure 4.2. Moisture content of organic forest floor layers in a black spruce forest through time.

Table 4.5. Monthly moisture content of litter and upper mineral soil as percent dry soil weight, mean monthly values with 95% confidence intervals, unpublished data (Van Cleve, per. com.).

Month	Observed Means		Simulated Values	
	Litter	Mineral	Litter	Mineral
6	153.31+/-12.91	64.60+/-5.96	176.38	60.98
7	160.69+/-10.79	49.84+/-3.48	160.50	54.31
8	151.28+/- 9.12	46.97+/-2.62	148.25	49.17
9	172.12+/-12.72	50.24+/-4.56	138.63	45.13

autumn evaporation is reflected in evapotranspiration (Table 4.2, page 35). The results do indicate reasonable values for mid-summer moisture levels and subsequent incorporation of ground thermal regime may further increase the accuracy of early and late available moisture levels.

The results of simulating moisture levels in black spruce forest soils (Fig. 4.2) approximated reported values (Dyrness and Norum 1983) although statistical comparisons were not appropriate.

CONCLUSIONS

It is apparent that further information concerning the actual evapotranspirational water losses from the forest soils in the Fairbanks is needed to validate simulations. The addition of deep mineral soil moisture dynamics to such a modeling approach would also require additional data. Until such information is available, more precise estimations of soil layer moisture content through time is limited.

CHAPTER 5

PERMAFROST DYNAMICS

INTRODUCTION

Permafrost influences forest succession through a number of pathways. It modifies soil temperature regime and increases overlying soil moisture content by limiting throughflow and providing meltwater during summer. It also serves as a mechanical barrier to root penetration, limiting the effective rooting depth to the thawed surface zone (active layer). Tree species distributions and productivities are highly correlated to permafrost distribution and active layer depth (Krause et al. 1959, Wilde and Krause 1960, Viereck 1965 and 1970, Dingman and Koutz 1974, Van Cleve and Viereck 1981). The primary difference between topographic locations of white (permafrost-free) and black (permafrost) spruce stands in the loess covered uplands near Fairbanks is aspect (Dingman and Koutz 1974, Van Cleve and Viereck 1981). The major climatic difference between these sites is available sunlight.

Many other factors also affect permafrost dynamics, such as soil bulk densities and moisture characteristics. Organic surface layers are especially important because of their insulating properties and high water holding capacities. Soil moisture content greatly affects thermal properties (De Vries and Afgan 1975, Salomone at al. 1982). Biotic factors of shading, litter production and moss accumulation are also significant (Dyrness 1982, Viereck 1982). The effects of these factors must be quantified to provide estimates of permafrost development and long term dynamics.

This chapter will present a computer subroutine which simulates permafrost dynamics based on climatic, edaphic and biotic characteristics of the boreal forests near Fairbanks.

RATIONALE

Information necessary for simulating permafrost dynamics is either directly available or can be calculated on the basis of available data. Monthly ambient temperatures and site-specific radiant energy are output from the AMBIEN subroutine (chapter 2) and the SUNLIT subroutine (chapter 3), respectively. Monthly precipitation values are available from long term climate records (NOAA 1977b) and soil moisture content through time is estimated by the MOIST subroutine (chapter 4). Shading, moss and litter accumulation data are available from information provided by the following sources.

1. Forest Soils Laboratory, University of Alaska, Fairbanks, Alaska,
2. Institute of Northern Forestry, USDA Forest Service, Fairbanks, Alaska, and
3. Forestry Sciences Laboratory, USDA Forest Service, Anchorage, Alaska.

Monthly estimates of site-specific light input, soil moisture regime and ambient conditions provide the means to calculate permafrost dynamics for a given site. Initial conditions of permafrost status and biotic characteristics may be specified. This approach has great flexibility and may be modified to fit a variety of environmental conditions.

METHODS

Ambient Freeze/Thaw Depths

Soil freeze/thaw depths were calculated monthly according to the Stephan formula for frost penetration in a multilayer soil system (Jumikis 1966), e.g., the number of freezing degree days necessary to freeze the third layer of a soil system is as follows.

$$DEGD = (Q/24)(R1 + R2 + R3/2)$$

$$Q = 80.0w$$

$$R = h/k$$

DEGD : Number of degree days required

Q : Heat of fusion of water (Cal)(m^{-3})

w : Water content (kg)(m^{-3})

R : Thermal resistance (m^2)(hr)(°C)(Cal^{-1}) of all layers

h : Soil layer depth (m)

k : Thermal conductivity (Cal)(m^{-1})(hr^{-1})($°C^{-1}$)

Climatically available freezing degree days were compared to degree day requirements for freezing each layer to determine monthly frost penetration. This approach assumes that a linear temperature gradient exists within each soil layer and that each layer has homogeneous thermal properties. Heat flow is assumed to be unidirectional and freezing occurs from the surface in a downward direction. Soils were assumed to thaw in an identical manner when melting degree days were available.

Thermal Conductivities

Soil thermal conductivities were estimated on the basis of dry soil density and moisture content, according to Kersten (1949). Thermal conductivities of unfrozen soils with densities greater than 0.5 g/cm^3 were calculated as follows.

$$k = (0.9\log(w) - 0.2)10^{RHO}$$

k : Thermal conductivity $(BTU)(ft^{-2})(hr^{-1})(in)(°F^{-1})$

w : Water content (percent dry soil weight)

RHO : Dry soil bulk density $(lbs)(ft^{-3})$

Conductivities of frozen soils (RHO > 0.5 g/cm^3) were estimated as follows.

$$k = .01(10)^{alpha} + .085(10)^{beta}w$$

alpha = 0.22RHO

beta = .008RHO

Conductivities were transformed to units of $(Cal)(m^{-1})(hr^{-1})\ (°C^{-1})$ for further calculations. Low density organic layers show a more linear increase in conductivity with increasing moisture content (De Vries and Afgan 1975, Salomone et al. 1982). A simple linear equation was used to calculate organic layer conductivities.

$$k = (c/s)w + b$$

c : Conductivity of water or ice

s : Saturation point of soil

w : Soil water or ice content

b : Dry soil conductivity

Sunlight Input

Dingman and Koutz (1974) found that permafrost-free sites with mature aspen, birch and/or white spruce received at least 106% of the horizontal incident radiation. This would correspond to a 7 degree slope for a south aspect (180 degrees) orientation, according to the SUNLIT subroutine (chapter 3). This observation was used to estimate the minimum net radiation heat input to an average soil profile of such a permafrost-free site.

Representative soil layer bulk densities, depths, and moisture holding characteristics of soils beneath a mature white spruce stand, a mature black spruce stand and a soil devoid of litter were based on provided data (Table 5.1). Simulated monthly soil moisture regimes were used to estimate conductivities and, with generated ambient temperatures, used to calculate soil freeze/thaw depths. Additional soil thawing due to sunlight heat was limited to summer months with

Table 5.1. Soil characteristics used in bare soil model simulations, depth in cm, density in g/cm^3, FC (field capacity) and SAT (saturation) in cm water/cm soil.

Layer	Depth	Density	FC	SAT
1	0-10	0.999	0.30	0.45
2	10-20	0.999	0.30	0.45
3	20-30	1.100	0.30	0.45
4	30-630	1.400	0.23	0.35

ambient temperatures greater than freezing. Heat flow through the soil profile was considered to be unidirectional and transferred according to simple heat conductance, e.g., heat transferred through a soil layer was calculated as follows.

$$Q = kat(Tu-Tl)/h$$

Q : Heat transferred
k : Thermal conductivity
a : Surface area
t : Time span
Tu : Upper layer temperature
Tl : Lower layer temperature
h : Depth of layer

A soil temperature profile was estimated on the basis of ambient temperature and depth of ambient induced ground thaw. A linear temperature gradient was assumed to exist between the soil surface (equal to ambient temperature) and the depth of thaw. Fairbanks lies in the discontinuous permafrost region which does not exhibit frozen ground temperatures much below -1°C (Wein and MacLean 1983), so this value was used as the lower limit to ground temperature.

Snow Insulation

Winter snow accumulation in the Fairbanks region provides a thick insulative layer, limiting soil frost penetration. The ratio of snow depth to equivalent water varies from about 5:1 to 14:1 for interior regions of Alaska (NOAA 1970-1980). A ratio of 10:1 was used in these simulations to estimate snow accumulation and a thermal conductivity of 0.15 (Cal)(m^{-1})(hr^{-1})($°C^{-1}$) was used to estimate thermal resistivity of the snow blanket through time. Snow melt was modeled similar to soil thawing and driven by available thawing degree days and incident sunlight. A snow depth of 100 cm (10 cm equivalent water) requires approximately ten degree days to melt. This is similar to observations on snowmelt reported by Kane et al. (1978).

Simulations

Freeze-thaw patterns of three basic soil-vegetation groupings were investigated, i.e., typical forest soils of mature white and black spruce and a bare mineral soil. All simulations were for a period of 110 years with the first 10 years deleted from statistical analyses. This was to allow time for soil moisture values to equilibrate. Each soil was modeled with a variety of deep soil moisture conditions specified, since the moisture routine (chapter 4) does not modify deep soil moisture content.

All white spruce forest soil simulations were initiated with a moist unfrozen soil profile. Sunlight input was estimated for a south aspect (180 degrees) slope (7 degrees) and soil freeze-thaw characteristics were estimated with and without sunlight energy input.

All black spruce simulations were also initiated with an unfrozen soil profile. Sunlight input was estimated for a north aspect (0 degrees) slope (30 degrees). All cases included the input of sunlight energy.

Both frozen and unfrozen initial soil profiles were used in simulations of bare mineral soil freeze-thaw cycles. Sunlight input was estimated for a north aspect slope.

RESULTS

White Spruce Stand

Results of 100-year simulations with full sunlight input showed that the depth of frost penetration was highly correlated to moisture content of lower soil layers (Table 5.2). Decreasing deep mineral soil moisture content from field capacity by 75% increased mean annual frost penetration depth from 62.87 cm to 129.97 cm. It also decreased the number of summers exhibiting persistently frozen soil from 9 to 2 of the 100 years. An average annual soil freeze-thaw cycle for this white spruce soil profile with 33% deep mineral soil moisture content shows complete thawing by August (Fig. 5.1).

Table 5.2. Mean frost penetration depth in white spruce forest soil profile, deep mineral soil moisture values as fraction of field capacity (FC).

Mineral Soil Moisture	Freeze Thaw	N	SE
Full Sunlight Input			
1.00 FC	62.87	91	1.0374
.50 FC	82.95	97	1.0553
.33 FC	105.27	98	1.3804
.25 FC	129.97	98	1.7692
No Sunlight Input			
.33 FC	110.06	100	1.5415

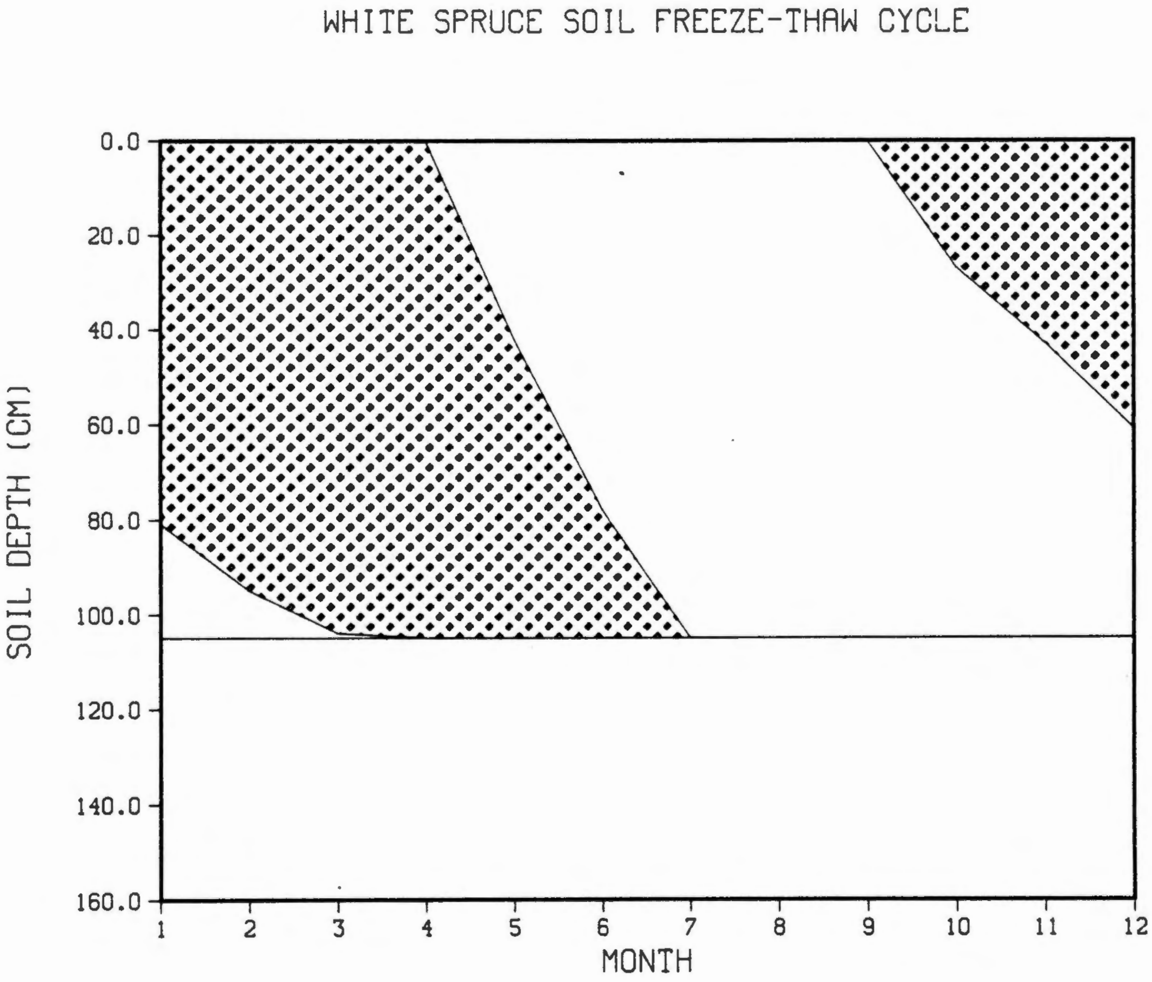

Figure 5.1. White spruce forest soil annual freeze-thaw cycle. Deep mineral soil moisture content at 33% field capacity, with full sunlight input. Stippled area represents frozen soil.

Sunlight energy flow through the soil litter layer was limited to about 3% of the total available sunlight (9602 (cal)(cm^{-2})(month^{-1})). This was due to the low litter thermal conductivity and narrow soil temperature profile (Table 5.3). However, when no sunlight was available, all years showed frozen ground persisting through the summers, with a mean annual thaw depth of 110.06 cm (Table 5.2).

Black Spruce Stand

Simulation results with full sunlight input showed that deep soil moisture content also affected annual freeze-thaw patterns in black spruce forest soils (Table 5.4). Decreasing mineral soil moisture content from saturation to half field capacity increased mean annual thaw depth from 55.30 cm to 101.96 cm (September mean values). An average annual freeze-thaw cycle shows maximum thaw depths achieved in September (Fig. 5.2). All simulations resulted in a net annual increase in permafrost thickness, so no runs were conducted with the absence of sunlight input.

Heat transfer through surface organic layers was again limited. Only approximately 1% of the total available energy (6527 (cal)(cm^{-2})(month^{-1})) transferred through the surface 10 cm moss mat. Soil temperature profiles were more abrupt than in the white spruce forest soil (Table 5.3).

Bare Soil

Simulations with full sunlight input and a fully frozen, water saturated mineral soil profile (630 cm total depth) required only 25 years to fully thaw. Modifying site slope and aspect had no

Table 5.3. Estimated soil temperature profiles (Centigrade degrees) for model simulations, depths are from the surface of the litter where present, June temperature values, ambient mean = 16.55, standard deviation = 0.9634.

Layer	Depth (cm)	White Spruce	Black Spruce	Bare Soil
1	0-10	14.69	12.89	12.81
2	10-20	12.75	9.27	8.92
3	20-30	10.82	5.63	5.02
4	30-630	-1.00	-1.00	-1.00

Table 5.4. Mean thaw depths in black spruce forest soil underlain with permafrost, mineral soil moisture values as fraction of field capacity (FC), all simulations including full sunlight input.

Mineral Soil Moisture	Thaw Depth (Sept)	N	SE
Saturated	55.31	100	0.3736
1.00 FC	68.92	100	0.7217
.50 FC	101.96	83	1.9299
.25 FC	145.61	92	2.0961

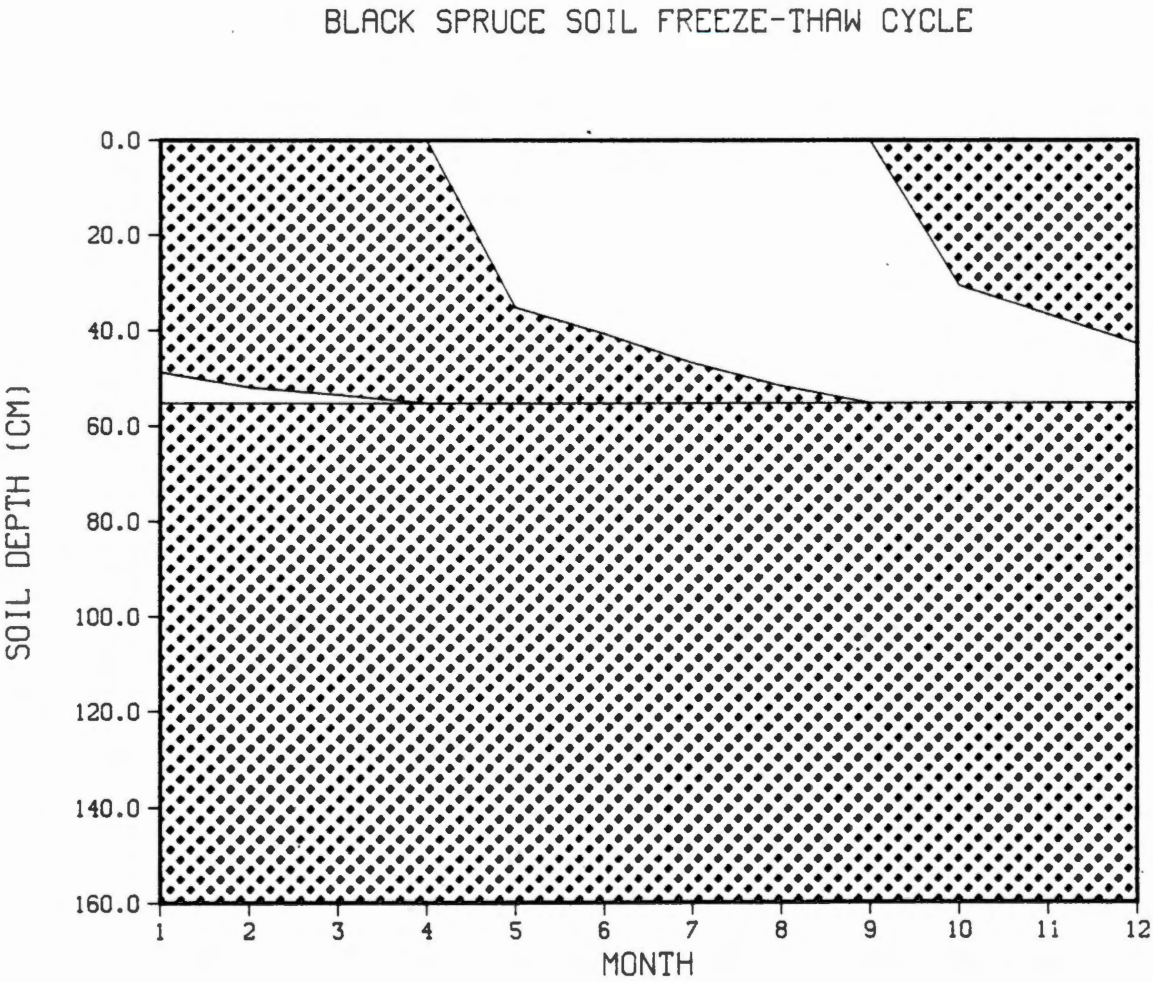

Figure 5.2. Black spruce forest soil annual freeze-thaw cycle. Deep mineral soil moisture content at saturation, with full sunlight input. Stippled area represents frozen soil.

significant effect on this thaw pattern. Sunlight energy transfer through soil layers was limited to 18% of the available energy (north slope).

Simulations without initial deep frozen soils showed that decreasing mineral soil moisture content from saturation to 33% field capacity increased annual frost penetration depth from 50.13 to 102.08 cm (Table 5.5). The annual freeze-thaw cycle under water saturated conditions was similar to the pattern for drier white spruce forest soils but with a smaller amplitude (Fig. 5.3).

DISCUSSION

Observed patterns of annual freeze-thaw cycles were matched by simulation when deep soil moisture characteristics were specified. Mean annual frost penetration depth in non-permafrost soil lies between 1.0 and 1.2 m (Kallio and Rieger 1969) which the model produced when deep mineral soil moisture values were set at 25 to 33% of field capacity. Mature black spruce forest soil thaw depths of 50 to 70 cm

Table 5.5. Mean frost penetration depth in bare soil profile without permafrost, deep mineral soil moisture values as fraction of field capacity (FC), all simulations including full sunlight input.

Mineral Soil Moisture	Freeze Depth (May)	N	SE
Saturated	50.54	95	0.7728
1.00 FC	60.96	97	0.9401
0.33 FC	102.08	98	1.3604

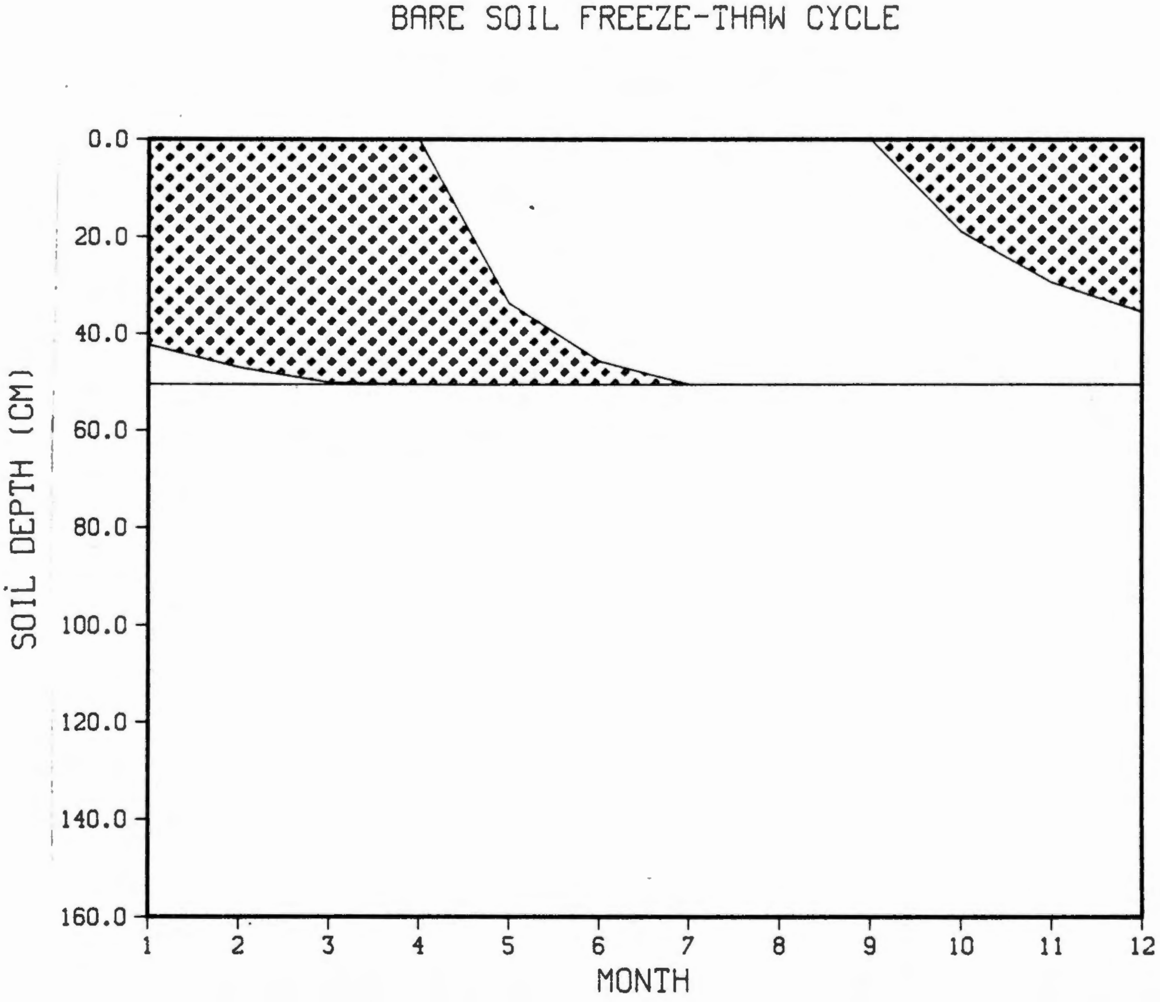

Figure 5.3. Bare mineral soil annual freeze-thaw cycle. Deep mineral soil moisture content at saturation, with full sunlight input. Stippled area represents frozen soil.

(permafrost soil) were matched when mineral soil moisture values were set at saturation. In both cases, simulated freeze-thaw depths matched reported values when mineral soil moisture was set at observed levels (Dyrness and Grigal 1979, Dyrness 1982, Viereck 1982, Viereck et al. 1983, Van Cleve unpublished material). Unfortunately, the mechanisms for obtaining and/or maintaining these moisture levels are unclear. Potential evapotranspirational losses are much higher than average precipitation (see chapter 4) so deep soil layer water input values are unknown. Vegetation is primarily rooted in the upper few centimeters of mineral soil (Viereck et al. 1983) so deep soil moisture losses are also difficult to estimate. Until further information concerning soil moisture dynamics is available, deep soil moisture levels must be set at specified values.

Estimated sunlight energy heat transfer into soil profiles was similar to values reported in the literature. Gold and Boyd (1965) found that only 2.8% of the net summer incoming solar radiation was actually stored in the ground for a horizontal grassy site in Ottawa, and McCaughey (1982) found that 1 to 15% of the net incoming radiation was used for soil heating in clearcuts in Quebec forests. Therefore, differences in available sunlight were insufficient to directly explain topographical variation in permafrost location.

Simulation results indicated that thick moss layers and high soil moisture content were highly correlated with permafrost development and/or maintenance. It was apparent that the total depth of the freeze-thaw cycle depended on the soil moisture content and that net freezing or thawing was determined by the quantity and qualities of the overlying organic layer(s). The mosses seemed to be the major factor linked to the existence of permafrost. Theoretically, any situation affecting soil moisture and moss production would influence soil freeze-thaw cycles. Unfortunately, there exists no obvious pathway of shifting between permafrost and non-permafrost soils in natural succession. Established permafrost with characteristically moist soils and thick moss mats is the result of long term development processes. Individual overlying forest stands are transitory by comparison. Until additional information concerning soil moisture dynamics and moss proliferation is available, simulating transitions between these two soil types under natural forest conditions will be limited. The observed melting of permafrost in cleared (or burned) black spruce stands was similar to model results (Viereck and Schandelmeier 1980, Dyrness 1982, Viereck 1982) and was directly correlated to losses of surface organic matter. Reestablishment of permafrost depth under such circumstances depends on total surface organic layer loss, regeneration of the forest stand and future moss establishment and production.

CONCLUSIONS

There were three major conclusions resulting from this modeling exercise:

1. the total depth of the freeze-thaw cycle in these soils was determined by the soil moisture content,
2. the net balance of freezing and thawing in these soils was determined by the qualities and quantities of the overlying organic layers, and

3. the difference in available sunlight was insufficient to directly explain topographical patterns of permafrost distribution.

Additional information concerning moisture dynamics of deep soil layers and moss proliferation is necessary to formulate a more general model than was possible with the present constraints. This would permit possible construction of pathways for transitions between permafrost and non-permafrost soils under natural conditions.

CHAPTER 6

FOREST SUCCESSION

INTRODUCTION

The forest modeling approach used in this study is similar to several earlier models (Botkin et al. 1972, Shugart and West 1977, Mielke et al. 1978, Shugart and Noble 1981, Weinstein et al. 1982). All incorporate species-specific characteristics of regeneration, growth and mortality. The overall success of this technique in simulating forest succession for a variety of forest types indicates its potential value for similar application to boreal systems (see chapter 1). This model requires a minimum of detailed climatic, edaphic and biological information. For these reasons, this approach was chosen as the framework for constructing a boreal forest succession model.

MODEL DESCRIPTION

All of these models share several basic equations. Since detailed explanations exist in the literature, a brief description of the common equations follows (Shugart and West 1977).

Growth

The growth of each tree is modeled as a function of climate, leaf area, competition, tree size and active layer depth. The optimal growth equation is as follows.

$$d(D^2H)/dt = RLA(1-(DH/DmaxHmax))$$

R : Growth rate parameter

LA : Leaf area (cm^2)

D : Diameter at breast height (cm)

H : Height of the tree (cm)

Dmax : Maximum species diameter (cm)

Hmax : Maximum species height (cm)

The height of the tree is estimated on the basis of dbh (Ker and Smith 1955).

$$H = 137 + b2D - b3D^2$$

The values of b2 and b3 were determined by setting H = Hmax (Botkin et al. 1972). Expected maximum heights and diameters for tree species in the research area, taken from the literature (Gregory and Haack 1965, Farr 1967, Viereck and Little 1972, Mead 1978) were compared to estimated values to ensure an adequate fit to observed growth curves.

$$b2 = 2(Hmax - 137)/Dmax$$

$$b3 = (Hmax - 137)/Dmax^2$$

Leaf area was calculated (Sollins et al. 1973).

$$LA = aD^{2.129}$$

$$a = 1.9283 \times 10^{-4}$$

To determine shading of an individual, the leaf areas of all taller trees were summed and the light extinction was calculated (Kasanaga and Monsi 1954, Loomis et al. 1967, Perry et al. 1969).

$$Q(h) = \exp(-k \int_{h}^{0} (LA(h')dh'))I$$

Q(h) : Radiation at height h

I : Incident radiation

k : A constant (0.25)

LA(h') : Distribution of leaf area over height

Botkin et al. (1972) present two equations expressing the reduction in photosynthesis for shade tolerant (Rs) and intolerant (Ri) trees.

$$Rs(AL) = 1-\exp(-4.64(AL-0.05))$$

$$Ri(AL) = 2.24(1-\exp(-1.136(AL-0.08))$$

AL : Available light

These functions fit photosynthesis curves (Kramer and Kozlowski 1960) scaled such that optimal light equals 1.0 (Shugart and West 1977).

Botkin et al. (1972) assumed that each species had an optimal temperature for growth and that growth rate decreased as a parabolic function for temperatures above and below this value.

$$T = 4(DEGD-DEGDmin)(DEGDmax-DEGD)/(DEGDmax-DEGDmin)^2$$

T : Value from 0.0 to 1.0

DEGD : Available growing degree days

DEGDmin : Minimum value in species range

DEGDmax : Maximum value in species range

Available growing degree days (DEGD) was used as an index to this thermal relationship (5°C base).

Growth reduction related to site specific maximum biomass limitation was calculated (Botkin et al. 1972).

$$S = 1 - BAR/SOILQ$$

S : Value from 0.0 to 1.0

BAR : Total stand biomass (t/ha)

SOILQ : Maximum biomass attainable

The results of the permafrost simulations (chapter 5) provide an additional factor influencing the growth equation. Species occurrence was correlated with active layer depth (Stoeckeler 1952) to formulate a relationship between growth potential and depth of active layer. A sigmoid response curve was considered most appropriate.

$$GM = ACTDPT^2/(ACTDPT^2 + ACTmin^2)$$

GM : Value from 0.0 to 1.0

ACTDPT : Active layer depth (cm)

ACTmin : Depth required for half growth potential (cm)

Individual tree biomass (g) was calculated on the basis of dbh (cm) as follows.

$$\ln(BIO) = alpha + beta(\ln(dbh))$$

BIO : Biomass (g)

Values of alpha and beta are species-specific (Van Cleve and Dyrness 1978).

Birth

The birth subroutine enters saplings to the simulation each year by comparing species requirements to existing conditions. All species require mineral soil seedbeds for successful seedling establishment. When conditions are favorable, the model selects species randomly and enters from 0 to 7 individuals (randomly determined) at an initial size of 1.27 cm dbh.

Sprout

Paper birch and aspen produce sprouts from stumps and roots, respectively. When an individual of either species dies, and is between minimum (SPRTMN) and maximum (SPRTMX) size limits for sprouting, then it is eligible to sprout that year. Although black spruce will reproduce vegetatively when surface moss/litter cover lower branch tips, this model did not include layering. The model randomly selects from eligible individuals and enters the appropriate number of sprouts per tree (SPRTNO) at 2.54 cm dbh.

Kill

Individual mortality can be modeled in two ways. The first assumes that only 2% of all individuals live to reach maximum age (AGEmax). Therefore, each year an individual has a constant probability of death. For example, the probability of death in a given year for a species with maximum age of 250 years is calculated as follows.

$$(1 - P)^{250} = 0.02$$

P : Annual probability of death (0.0 to 1.0)

The second method assumes that trees must maintain a minimum level of sustained growth (at least 0.1 cm dbh increment). If an individual falls below that level, it is marked as supressed and is subjected to increased mortality. Only 1% of intolerant species, i.e., birch and aspen, are expected to survive a maximum of ten years in a supressed state. Black and white spruce, however, are extremely tolerant and may survive up to 150 years of supression. In all cases, individual death is determined at random each year.

Fire

Annual stand mortalities were estimated in a manner identical to individual tree mortality (see above). Since fire cycles vary between forest types, it was assumed that 20% of the forest stands were expected to survive their characteristic fire cycle. This was 200 years for white spruce/deciduous stands and 100 years for black spruce. These values are compatible with reported observations for the area (Viereck and Schandelmeier 1980).

Organic Layers

The accumulation of forest floor organic matter was estimated according to linear regressions derived from data presented by Viereck et al. (1983). White spruce/deciduous stands accumulate forest floor litter at about 0.0570 cm/year ($N = 8$, $R^2 = 0.9123$). Black spruce forests accumulate surface organic material at approximately 0.0996 cm/year ($N = 8$, $R^2 = 0.7747$).

In the event of a fire, white spruce/deciduous forest floors were considered entirely consumed. Black spruce forest floor depths were reduced according to Dyrness and Norum (1983).

$$Y = -6.6 + 0.76(X1) - 0.048(X3) - 0.047(X5)$$

Y : Depth removed (cm)

X1 : Preburn total depth (cm)

X3 : Moisture content of fabric layer

X5 : Moisture content of duff layer

Moisture values as percent dry soil weight

If the necessary layers did not exist for use in the above equation, organic matter consumption was estimated as a linear function of moisture content, with no loss at field capacity and full consumption when totally dry. These organic layer depth modifications were reflected in subsequent moisture and freeze-thaw calculations.

Species Characteristics

Individual characteristics explained in the text are listed by species (Table 6.1).

METHODS

Initial Conditions

Two initial sets of conditions were specified for model runs, representing white spruce/deciduous (permafrost-free) and black spruce (permafrost) forest soils. Simulations began with the "best result" soil conditions specified in chapters 4 and 5, i.e., 10 cm each litter and A0 horizon at field capacity over 610 cm mineral soil at 33% field

Table 6.1. Specific species' characteristics presented in the text (see text for units and references), species codes are B.p. : [*Betula papyrifera*], P.g. : [*Picea glauca*], P.m. : [*Picea mariana*], and P.t. : [*Populus tremuloides*].

Parameter	B.p.	P.g.	P.m.	P.t.
AGEmax	140	200	250	130
DEGDmax	2036	1911	1911	2461
DEGDmin	484	280	247	743
ACTmin	60.96	121.92	10.00	182.88
alpha	5.18	3.35	3.63	4.51
beta	2.15	2.66	2.54	2.43
SPRTND	1	0	0	5
SPRTMN	10	-	-	20
SPRTMX	30	-	-	130
Tolerance	Ri	Rs	Rs	Ri
b2	79.59	88.40	150.01	100.53
b3	0.5440	0.5801	2.7342	0.8680

capacity for white spruce (permafrost-free) sites, and 10 cm each moss, fiber and humus at field capacity over 600 cm mineral soil at saturation for black spruce (permafrost) sites. The permafrost-free site began entirely unfrozen while the permafrost site began entirely frozen. In both cases, seedlings were permitted to establish on the intact forest floor in model year 1.

Simulations

Both simulations were run for 1000 years and each consisted of 25 individual plots. Initial runs indicated that a fire cycle of 100 years was too short for maintenance of black spruce so the cycle was lengthened to 200 years for this site. Output consisted of yearly values of biomass, leaf area, number of stems, active layer depth and organic forest floor depth. The simulated stands were divided into 20-year age classes from which stand total and species-specific characteristics were summarized. Comparisons were made to biomass and density information provided by the Institute of Northern Forestry (INF) for upland forest stands in the Fairbanks area.

Comparative Data

Analyses of stand data provided by INF were used to assess the accuracy of the model. Stand information was divided into plots containing black spruce and plots containing other species since there was no consistent indication of permafrost presence. Data included stem dbh, species identification and distance measurements used to estimate stand densities by the point quarter method (Cottam and Curtis 1956). Stands were divided into 20-year age classes from which total and species-specific characteristics were summarized. These values were then compared to simulated output.

RESULTS

Combined Plots

Simulation results for the permafrost-free sites showed a steady increase in the relative contribution of white spruce to the total stand biomass with increasing stand age (Appendix A.1). White spruce biomass increased from 15% to 74% of the total stand biomass from 20 years to 200 years. During this time, birch biomass decreased from 69% to 25% of the total. Black spruce never represented a significant proportion of the total stand biomass and aspen decreased from 16% to less than 1% of the total between years 20 and 60. Summaries of the

INF data showed white spruce with low biomass contributions between 40 to 60 years, increasing to over 80% of the total stand biomass between years 160 and 200 (Appendix A.2). Birch and aspen showed very irregular biomass patterns over stand age but summing their relative contributions showed a large combined biomass (over 80% of the total) between years 40 and 60, decreasing to less than 20% by 160 years.

Total simulated stand biomass values increased from an initial 30 t/ha at 20 years to 80 t/ha at 60 years, declining to 36 t/ha by year 200. Total tree densities decreased exponentially from about 4800 stems/ha in year 20 to about 270 stems/ha in year 140. Densities then increased to about 360 stems/ha by year 200. The INF data showed total stand biomass values increasing from 16 t/ha at 20 years to about 80 t/ha by 120 years and about 140 t/ha between years 160 and 200. Stand densities decreased from 1800 stems/ha at 40 years to about 600 stems/ha between years 160 to 200.

Simulation results for the permafrost sites showed a significant effect of modifying critical active layer depth requirements (ACTmin) on species dominance patterns. The initial simulation values (see Table 6.1) resulted in birch with 43%, black spruce with 44% and white spruce with 12% of the total stand biomass at 200 years (Appendix A.3). Increasing the critical active layer depth from 60.96 cm to 121.92 cm for birch altered the simulation results. Birch then showed 2%, black spruce showed 77% and white spruce showed 20% of the stand total biomass at 200 years (Appendix A.4). Increasing critical active layer depths for birch and white spruce to 182.88 cm further affected dominance patterns. Birch then showed 1%, black spruce showed 94% and white spruce showed 4% of the total stand biomass at 200 years (Appendix A.5).

Summaries of the INF data showed black spruce relative biomass increasing erratically from 17% of the total stand biomass at 40 years to values ranging from 53% and 100% between years 80 and 200 (Appendix A.6). Birch showed consistently low values, averaging about 6% of the total biomass for all age classes, while aspen had a maximum biomass contribution of 71% at 40 years, decreasing to about 5% of the total within another 20 years. The single exception to this pattern was at 140 years, when the combined birch and aspen biomass totalled 38% of the total stand biomass.

Total simulated stand biomass values increased from 3 t/ha at 20 years to 14 t/ha at 80 years and then declined to 3 t/ha by year 200, for the run with the greatest species-specific active layer depth requirements (Appendix A.5). Tree densities decreased from about 4300 stems/ha initially, to about 380 stems/ha by year 140 and then increased to about 770 stems/ha by year 200. Simulation results with the lowest active layer depth requirements showed an increase in total stand biomass from 12 t/ha at 20 years to 39 t/ha at 60 years, decreasing to 5 t/ha by year 200 (Appendix A.3). Stem densities decreased from about 4300 stems/ha at 20 years to about 340 stems/ha at 140 years, then increased to about 890 stems/ha by year 200.

The INF data showed total stand biomass values increasing from 7 t/ha at 20 years to an average of 15 t/ha to 20 t/ha between years 40 to 120 (Appendix A.6). Peak values of about 35 t/ha to 40 t/ha were achieved between years 120 and 160. Values for years 180 to 200 seemed unreasonable. Stem densities increased from about 650 stems/ha at 20 years to about 2800 stems/ha at 100 years and continued to remain above 1000 stems/ha.

The permafrost-free site showed an active layer depth remaining at essentially the total soil depth through time. Organic layer depth increased linearly from about 1 cm at 20 years to 11 cm at 200 years. Changes in relative species abundances on permafrost sites correlated with differences in active layer depths and organic matter depths. The simulation with lowest black spruce dominance showed a slightly greater active layer depth and lower organic matter depth throughout the simulation (Appendix B.1) than did the forest with the greatest black spruce dominance (Appendix B.2).

Single Plots

Examining a single representative plot provides more information on the forest dynamics of the site than a composite of all 25 plots. Therefore, one plot was selected from each forest type for comparisons. Since the same fire frequency was used in both runs, the patterns of change in both forests were parallel, further aiding comparison.

The total number of stems was similar for both forest types. The permafrost site produced an average of about 4800 to 5400 stems/ha immediately following fire while the non-permafrost site produced 5400 to 6000 stems/ha. In both cases, this number decreased rapidly (Fig. 6.1). Total biomass did significantly differ between the the two types with the former attaining a maximum of about 45 t/ha (Fig. 6.2),

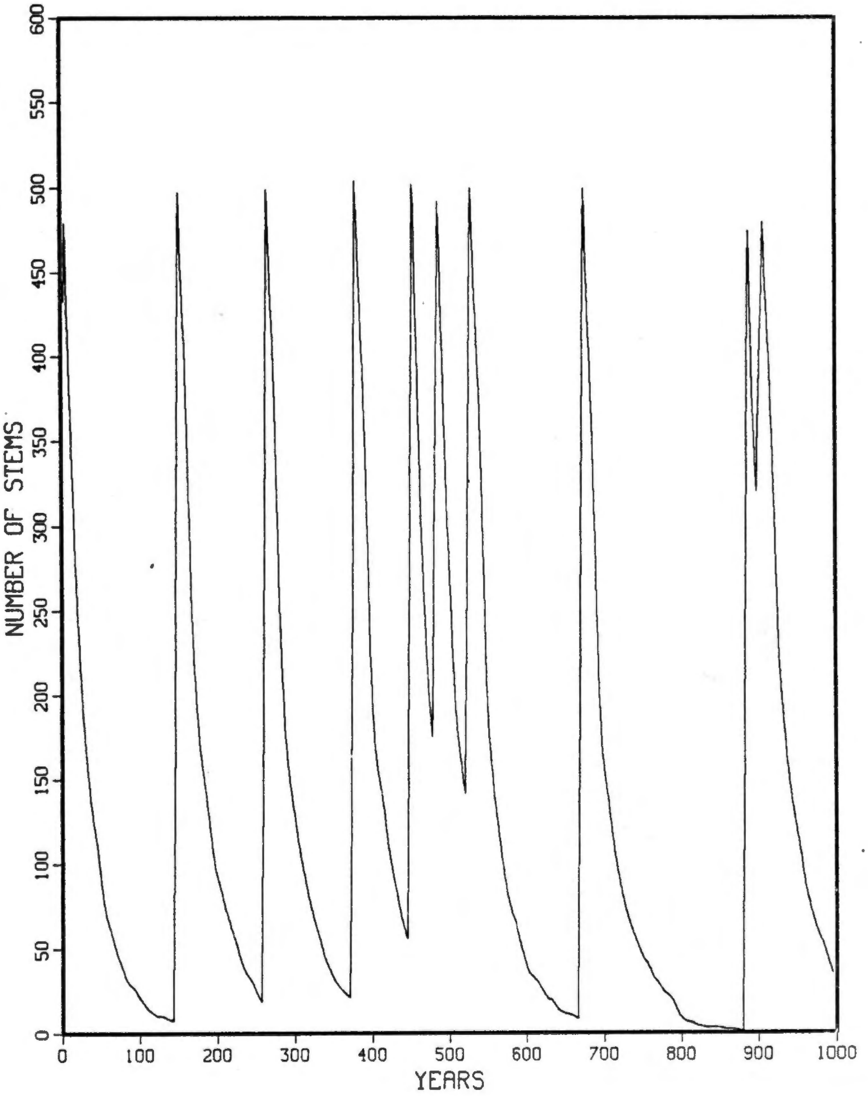

Figure 6.1. Simulated permafrost-free site stem counts (stems)/(1/12 ha) through time. Single plot.

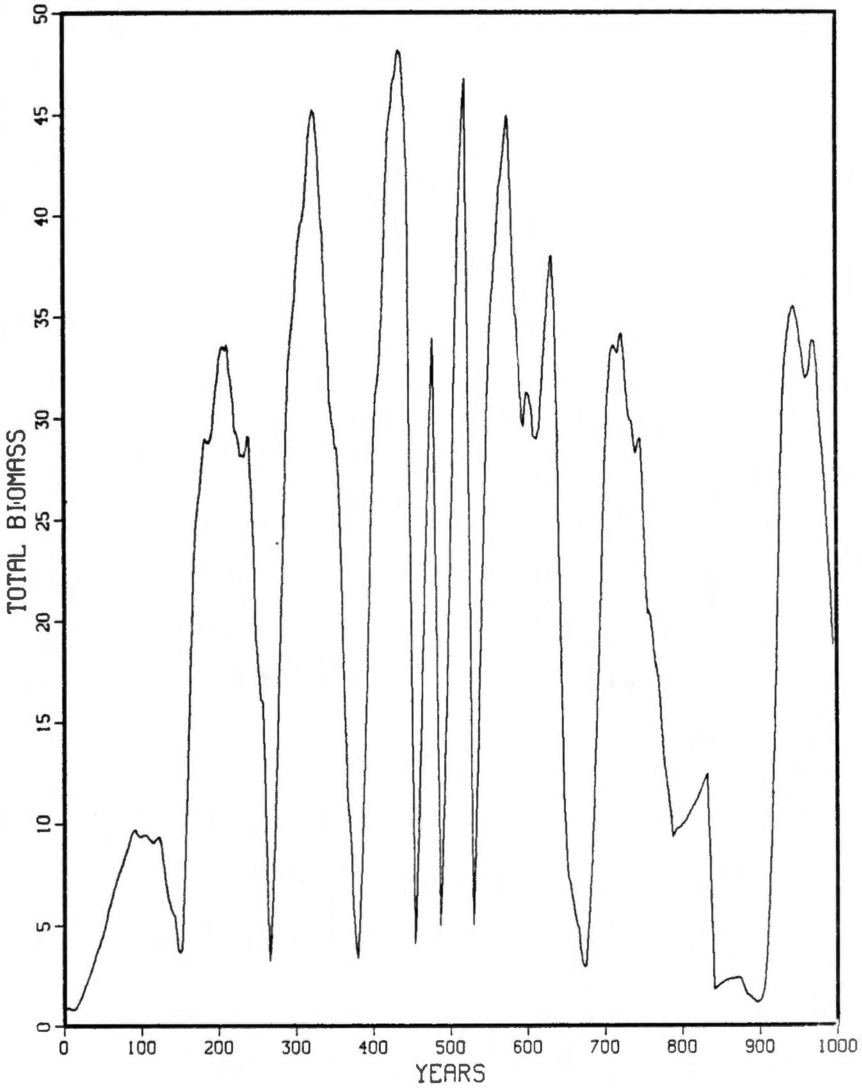

Figure 6.2. Simulated permafrost site total stand biomass (t/ha) through time. Single plot.

approximately half that of the latter (Fig. 6.3). Leaf areas showed a similar pattern with the permafrost site attaining maximum values of 4.5 to 5.0 while the more productive site consistently achieved values of 8.0 to 8.5 (Fig. 6.4).

Composite plots of relative species dominance (proportion of total biomass) showed similar succession patterns for both forest types. Birch predominated early succession and was eventually replaced by spruce, unless a fire intervened. On the more productive site (Fig. 6.5) white spruce attained approximately 50% of the total stand biomass approximately 100 years after disturbance and approached total dominance at 125 to 150 years. Aspen showed early establishment following fire but soon disappeared. Black spruce initially dominated the other site but subsequent fires established the predominance of birch through the majority of simulation years (Fig. 6.6). White spruce represented the majority of the stand biomass between simulation years 630 to 660 and black spruce did not become dominant again until years 830 to 900.

Active layer depth was essentially equal to the total soil depth throughout the simulation on the permafrost-free site. The accumulation of surface litter had little or no effect on this value. The permafrost site showed significant fluctuations of active layer depth through time (Fig. 6.7) which corresponded to changes in organic layer depth (Fig. 6.8).

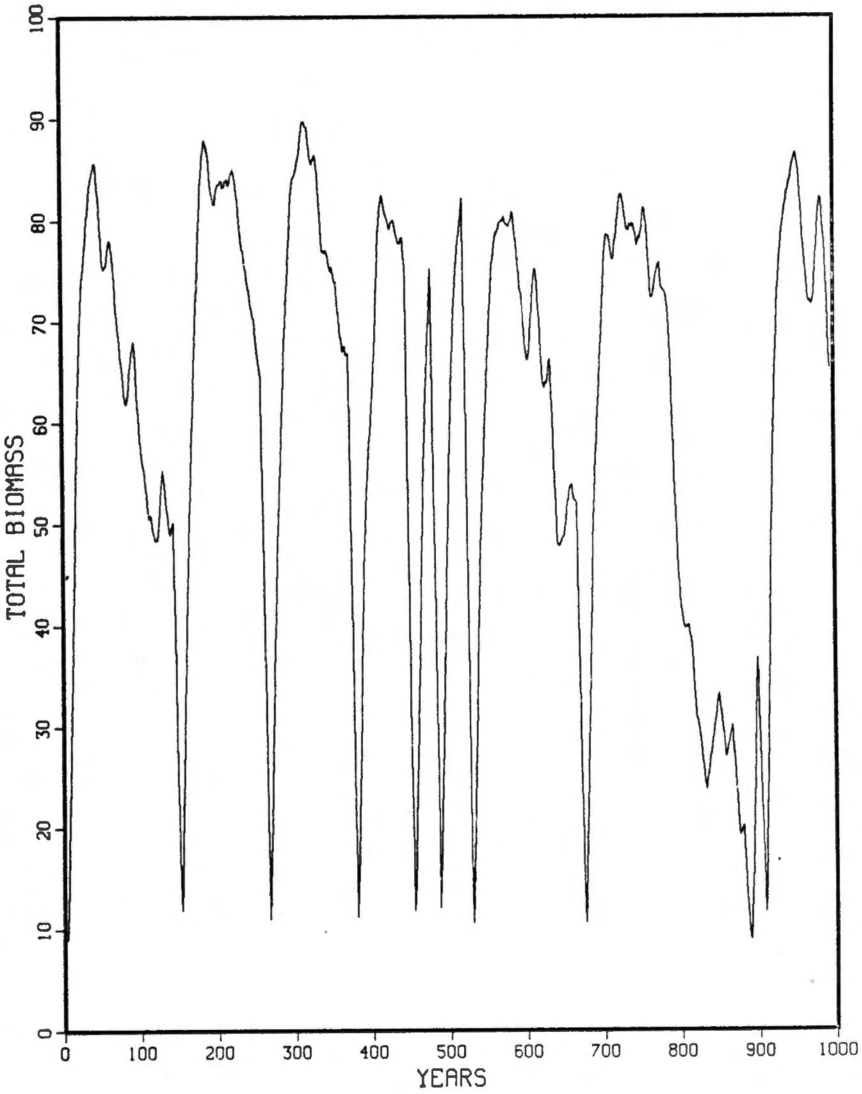

Figure 6.3. Simulated permafrost-free site total stand biomass (t/ha) through time. Single plot.

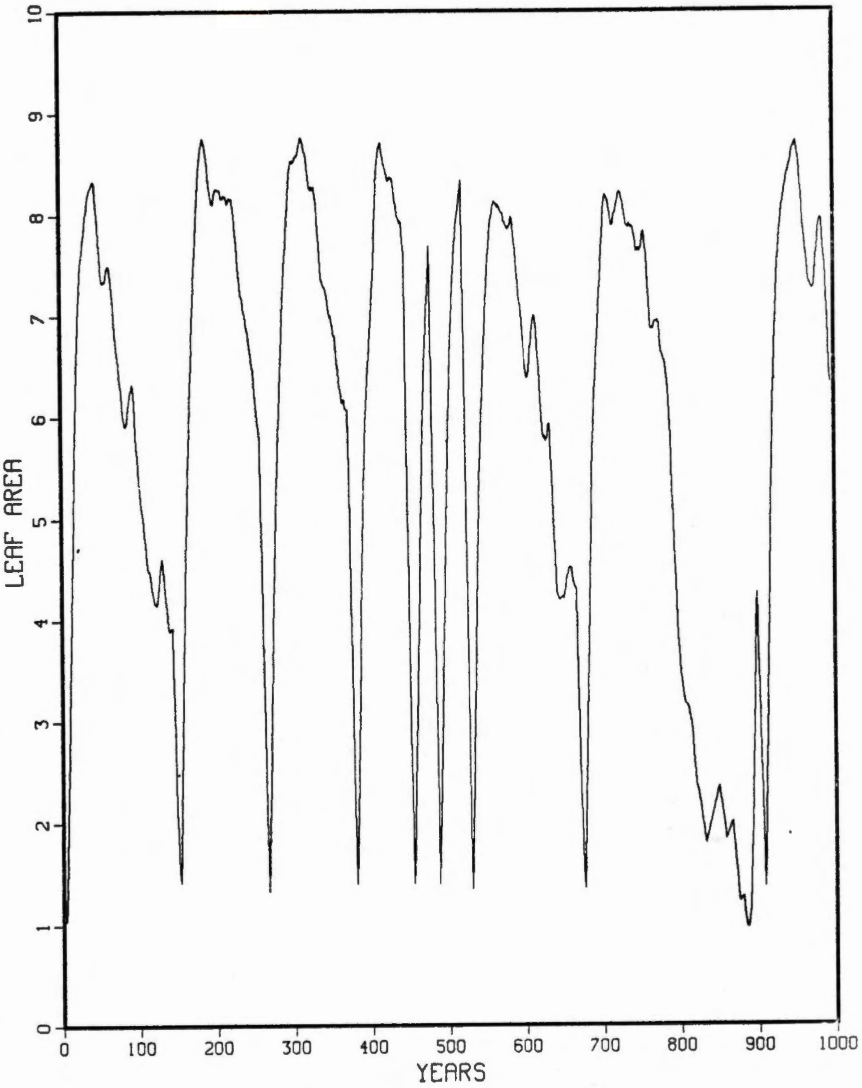

Figure 6.4. Simulated permafrost-free site total leaf area index through time. Single plot.

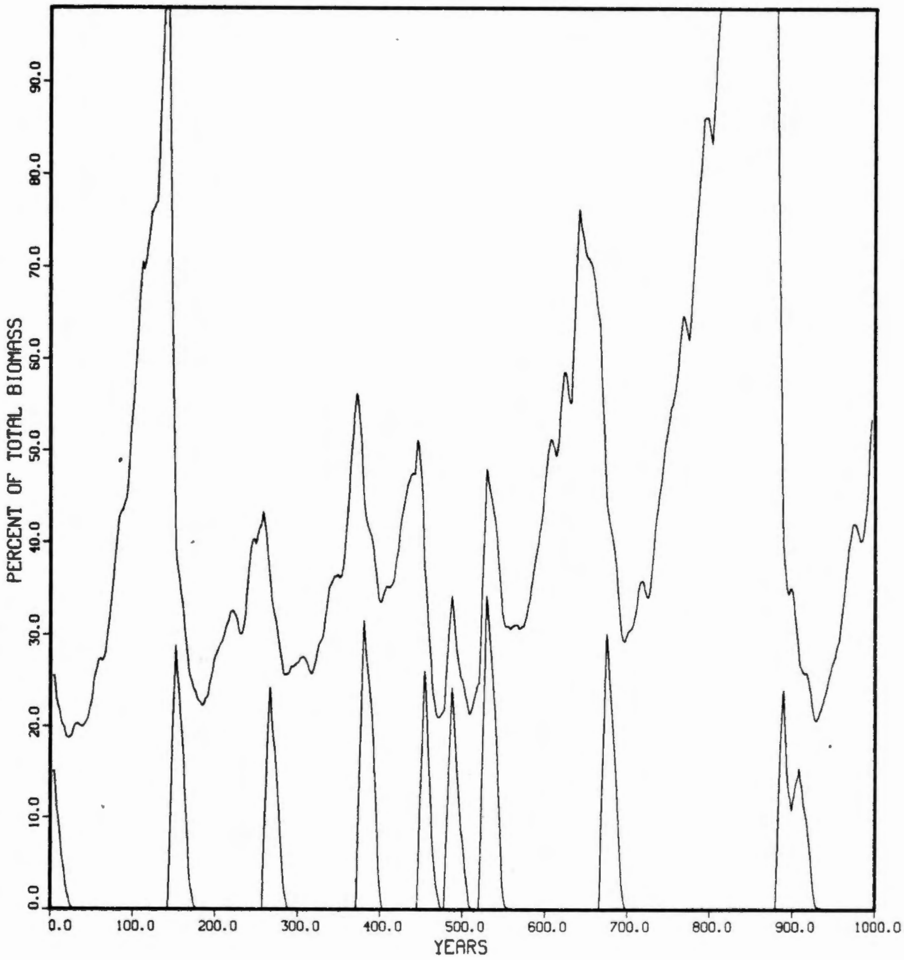

Figure 6.5. Simulated species relative biomass contribution (percent of total) on the permafrost-free site. Area between curves defines percent biomass. Birch: upper area, white spruce: middle area, aspen: lower area. Single plot.

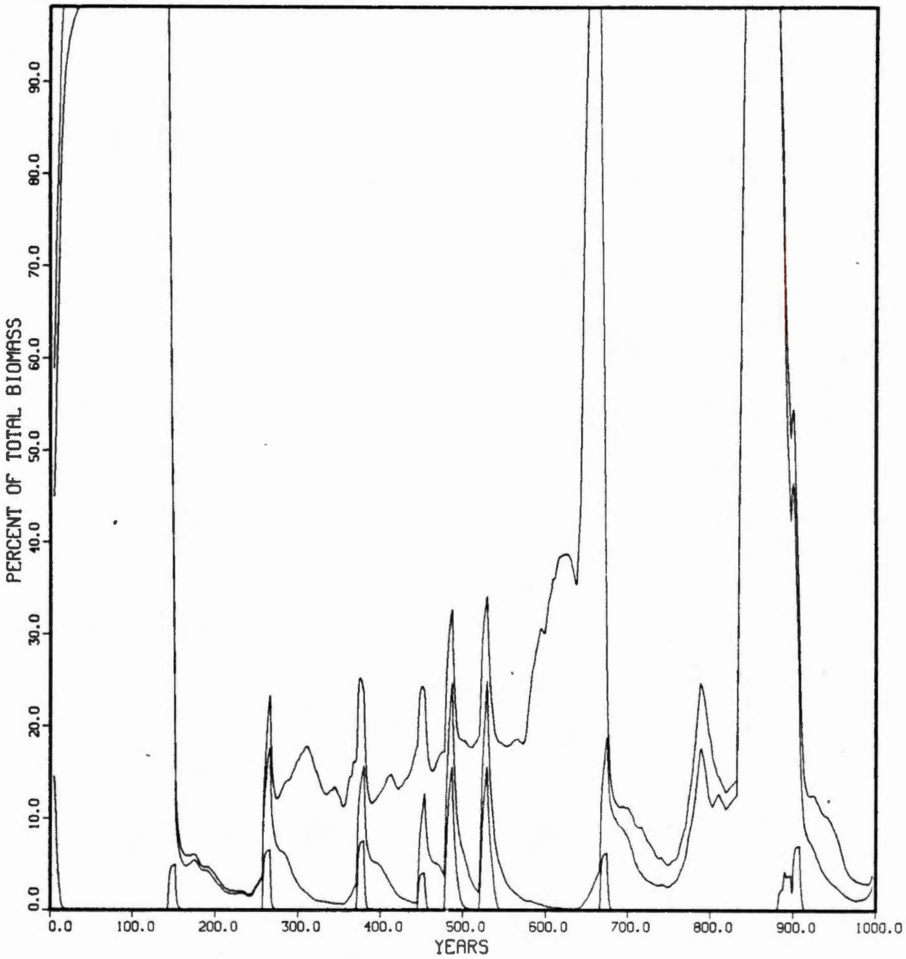

Figure 6.6. Simulated species relative biomass contribution (percent of total) on the permafrost site. Area between curves defines percent biomass. Birch: upper area, white spruce: upper middle area, black spruce: lower middle area, aspen: lower area. Single plot.

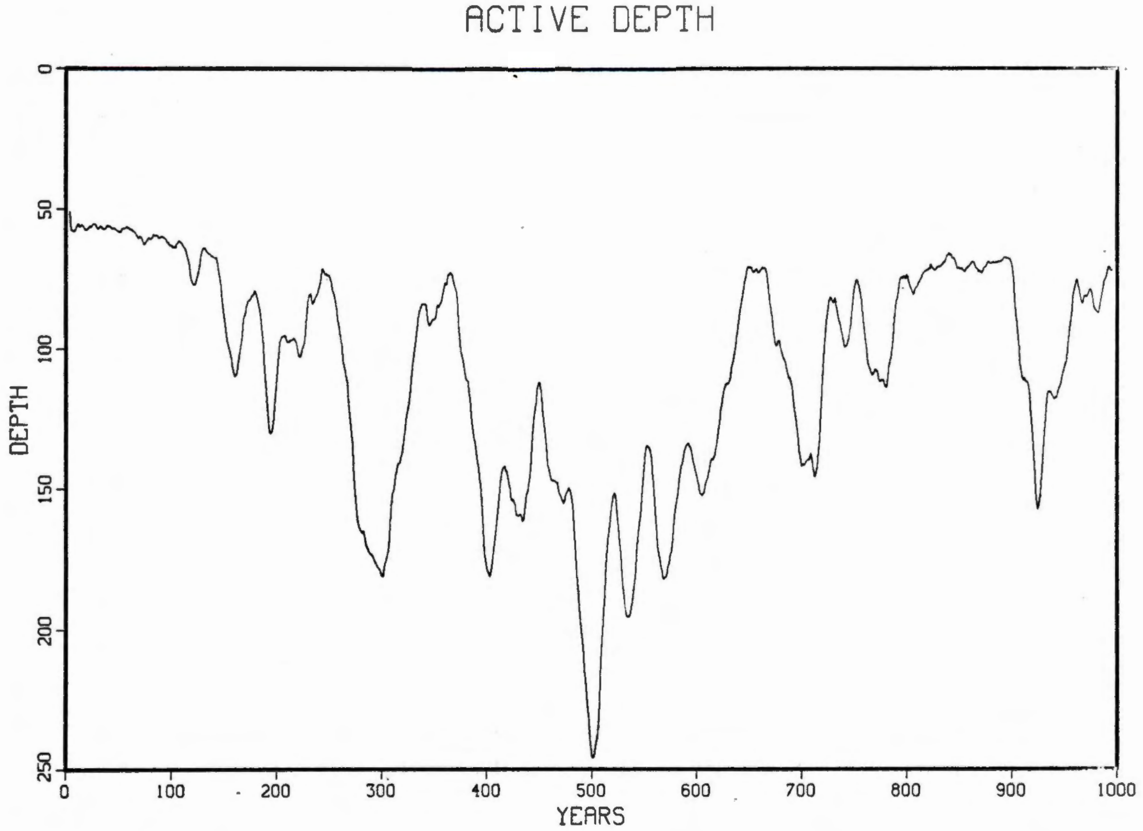

Figure 6.7. Simulated permafrost site active layer depth (cm) through time. Single plot.

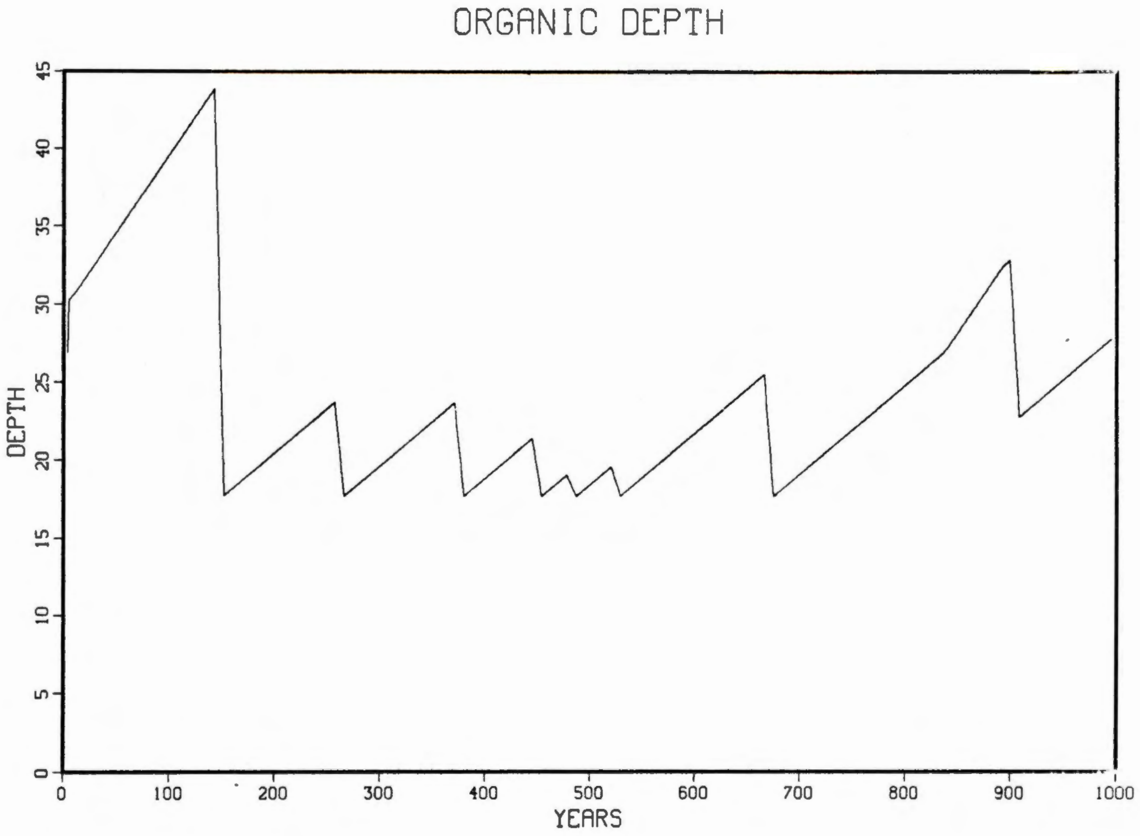

Figure 6.8. Simulated permafrost site organic layer depth (cm) through time. Single plot.

DISCUSSION

Combined Plots

Simulations on both sites produced forest succession patterns that were very similar to those in the provided data, once the species-specific active layer depth values were modified for the permafrost sites. Although stem counts and total biomass values were low in the simulations, the relative contributions of the various species to total stand biomass during succession were close to the reported patterns. Increasing both overall biomass and stand densities can easily be accomplished by modifying the maximum stand biomass limit, increasing survivorship and permitting a greater degree of regeneration on non-mineral soils. The major goal of simulating patterns of species dominance through time was reasonably well achieved. Aspen was not maintained in the simulations probably due to the lack of simulated moisture stress effects on competition. Aspen presence corresponds to warmer, drier sites (Van Cleve and Dyrness 1979, Viereck et al. 1983), and may succeed there due to greater drought tolerance than birch. However, combining aspen and birch biomass components in both the simulations and in the INF data produced similar patterns of net biomass contribution during succession.

There may have been some error in the analyses of the INF data since there was insufficient information to classify individual stands into permafrost and permafrost-free sites with any degree of certainty, individuals less than 2.4 cm dbh were not inventoried, there were a large number of zero counts for species, which affected the summarization output, and the data set was probably not a random sampling of the upland boreal forest system. Viereck et al. (1983) present mean standing biomass values for pure stands of 50 t/ha for black spruce, 174 t/ha for white spruce, 111 t/ha for aspen and 112 t/ha for paper birch.

Single Plots

Simulated succession on permafrost-free sites resulted in patterns similar to reported observations. Birch initially dominated after disturbance and was eventually replaced by white spruce (Fig. 6.5, page 75). The succession patterns produced in the black spruce (permafrost) site simulation showed obvious correlations between species dominance, active layer depth and soil surface organic matter accumulation (Figs. 6.6, 6.7 and 6.8). Between simulation years 300 and 700 there were several fires which resulted in decreased organic matter depth, increased active layer depth and the predominance of birch and white spruce. White spruce gained dominance only after the active layer depth had increased significantly and there was a long fire interval. Black spruce regained dominance when an additional long fire interval permitted organic matter accumulation and decreased active layer depth.

The inability of the black spruce system to maintain a predominantly black spruce forest at the 100 year fire cycle may have been due to several factors. Much of the dynamics for development, maintenance and loss of surface organic materials is poorly understood. Estimating organic layer consumption by fire is difficult (Dyrness and Norum 1983). The total organic depth in the black spruce site simulation never approached total consumption due to the different fire processes built into the model. With a standing forest of white spruce and/or deciduous species the fire routine simply removed the top layer of organic matter, not considering deeper fibric and humic layers. This artificially maintained a surface organic mat which probably influenced soil freeze-thaw cycles. This was the direct result of establishment of birch and white spruce on permafrost sites. It was apparent that the species-specific growth potentials estimated on the basis of active layer depth were too high for birch and white spruce. It would be very unlikely that these species would dominate the permafrost site as simulated. Unfortunately, there is no information available for establishing more accurate species-specific growth relationships.

It was apparent that the soil freeze-thaw balance behaved in an expected manner, fluctuating with changes in surface organic matter. Simulation results generally agreed with reported observations (see chapter 5).

CONCLUSIONS

The results of this investigation indicated that succession patterns for the upland boreal forest could be produced by the described model. The dynamics of organic layer depth and active layer depth were realistic and very closely matched observations for these forest types. Additional refinements which would increase the accuracy of this model include the following:

1. inclusion of drought stress estimations and effects on species competition,

2. better estimations of active layer depth effects on species-specific growth potentials,
3. additional information on forest floor organic matter accumulation, maintenance and fire consumption,
4. additional detailed observations on moisture and temperature regimes, especially for deep mineral soils,
5. determinations of actual thermal characteristics of organic soil components and their relationships to moisture content, and
6. determination of the effects of incident sunlight on moss proliferation.

LIST OF REFERENCES

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Barkstrom, B. 1981. What time does the sun rise and set? Byte. 6:94-114.

Barney, R. J., C. D. Bevins and L. S. Bradshaw. 1981. Forest floor fuel loads, depths, and bulk densities in four interior Alaskan cover types. United States Department of Agriculture. Forest Service Research Note INT-304.

Blackburn, W. 1982. Estimation of diffuse radiation components under partial cumulus cloud cover. Solar Energy 29:441-443.

Botkin, D. B., J. F. Janak and J. R. Wallis. 1972. Some ecological consequences of a computer model of forest growth. Journal of Ecology 60:849-872.

Brix, H. 1979. Effects of plant water stress on photosynthesis and survival for four conifers. Canadian Journal of Forest Research 9:160-165.

Bryson, R. A. and F. K. Hare (ed). 1974. Climates of North America. Elsevier Scientific Publishing Co. New York. 420 pp.

Cottam, G. and J. T. Curtis. 1956. The use of distance measures in phytosociological sampling. Ecology 37:451-460.

De Vries, D. A. and N. H. Afgan (eds). 1975. Heat and mass transfer in the biosphere. Part 1. Transfer processes in the plant environment. John Wiley and Sons. New York. 594 pp.

Dingman, S. L. 1971. Hydrology of the Glenn Creek watershed Tanana River basin, central Alaska. Cold Regions Research and Engineering Laboratory. Research Report. No. 297. Hanover, New Hampshire.

Dingman, S. L. and F. R. Koutz. 1974. Relations among vegetation, permafrost and potential insolation in central Alaska. Arctic and Alpine Research 6:37-42.

Doyle, T. W., H. H. Shugart and D. C. West. 1980. FORICO: Gap dynamics model of a lower montane rain forest in Puerto Rico. ORNL/TM-8115. Oak Ridge National Laboratory. Oak Ridge, Tennessee.

Dyrness, C. T. and D. F. Grigal. 1979. Vegetation-soil relationships along a spruce forest transect in interior Alaska. Canadian Journal of Botany 57:2644-2656.

Dyrness, C. T. 1982. Control of depth to permafrost and soil temperature by the forest floor in black spruce/feathermoss communities. USDA Forest Service. Research Note PNW-396.

Dyrness, C. T. and R. A. Norum. 1983. The effects of experimental fires on black spruce forest floors in interior Alaska. Canadian Journal of Forest Research 13:879-893.

Eis, S. 1967. Establishment and early development of white spruce in the interior of British Columbia. Forestry Chronicle 43:174-177.

Erbs, D. G., S. A. Klein and J. A. Duffie. 1982. Estimations of the diffuse radiation fraction for hourly, daily and monthly-average global radiation. Solar Energy 28:293-302.

Farr, W. A. 1967. Growth and yield of well-stocked white spruce stands in Alaska. United States Department of Agriculture. Forest Service Research Paper PNW-53.

Foote, J. M. 1983. Classification, description, and dynamics of plant communities after fire in the taiga of interior Alaska. United States Department of Agriculture. Forest Service Research Paper PNW-307.

Gloyne, R. W. 1965. A method for calculating the angle of incidence of the direct beam of the sun on a plane surface of any slope and aspect. Agricultural Meterology 2:401-410.

Gold, L. W. and D. W. Boyd. 1965. Annual heat and mass transfer at an Ottawa site. Canadian Journal of Earth Sciences 2:1-10.

Gregory, R. A. and P. M. Haack. 1965. Growth and yield of well-stocked aspen and birch stands in Alaska. United States Department of Agriculture. Forest Service Research Paper NOR-2.

Grigal, D. F. 1979. Extractable soil nutrients and permafrost under adjacent forest types in interior Alaska. Northwest Science 53:43-50.

Hagenstein, W. D. 1977. Industry looks at the forest products potential of interior Alaska. pp. 261-270. IN North American forest lands at latitudes north of 60 degrees, Symposium Proceedings. University of Alaska, Fairbanks.

Hatfield, J. L., R. B. Giorgis, Jr. and R. G. Flocchini. 1981. A simple solar radiation model for computing direct and diffuse spectral fluxes. Solar Energy 27:323-329.

Heilman, P. E. 1968. Relationship of availability of phosphorus and cations to forest succession and bog formation in interior Alaska. Ecology 49:331-336.

Hutchinson, O. K. and D. R. Schumann. 1976. Alaska's interior forests-Timber resources and utilization. Journal of Forestry 47:338-341.

Iqbal, M. 1980. Prediction of hourly diffuse solar radiation from measured hourly global radiation on a horizontal surface. Solar Energy 24:491-503.

Jumikis, A. R. 1966. Thermal soil mechanics. Rutgers University Press. New Brunswick, New Jersey. 267 pp.

Kallio, A. and S. Rieger. 1969. Recession of permafrost in a cultivated soil of interior Alaska. Soil Science Society of America Proceedings 33:430-432.

Kane, D. L., R. D. Seifert, J. D. Fox and G. S. Taylor. 1978. Snowmelt-frozen soil characteristics for a subarctic setting. University of Alaska. Institute of Water Resources Report 84. 64 pp.

Kasanaga, H. and M. Monsi. 1954. On the light-transmission of leaves and its meaning for the production of matter in plant communities. Japan Journal of Botany 14:302-324.

Ker, J. W. and J. H. G. Smith. 1955. Advantages of the parabolic expression of height-diameter relationships. Forestry Chronicles 31:235-246.

Kersten, M. S. 1949. Thermal properties of soils. University of Minnesota. Institute of Technology. Bulletin 28. 225 pp.

Klein, S. A. 1977. Calculation of monthly average insolation on tilted surfaces. Solar Energy 19:325-329.

Kozlowski, T. T. 1976. Water deficits and plant growth. Academic Press. New York.

________. 1982. Water supply and tree growth. Part III. Flooding. Forest Abstracts 43:145-161.

Kramer, P. J. and T. T. Kozlowski. 1960. Physiology of trees. McGraw-Hill Book Company. New York.

Kramer, P. J. and T. T. Kozlowski. 1979. Physiology of woody plants. Academic Press. New York.

Krause, H. H., S. Rieger and S. A. Wilde. 1959. Soils and forest growth on different aspects in the Tanana watershed of interior Alaska. Ecology 40:492-495.

Kusuda, T. and K. Ishii. 1977. Hourly solar radiation data for vertical and horizontal surfaces on average days in the United States and Canada. United States Department of Commerce. National Bureau of Standards Building Science Series No. 96.

Larsen, J. A. 1980. The boreal ecosystem. Academic Press. Physiological Ecology Series. New York, New York. 490 pp.

Lee, R. 1962. Theory of the "equivalent slope". Monthly Weather Review 90:165-166.

Lee, R. and A. Baumgartner. 1966. The topography and insolation climate of a mountinous forest area. Forest Science 12:258-267.

Lietzke, D. A. Department of Plant and Soil Sciences. University of Tennessee. Knoxville, Tennessee.

Liu, B. Y. H. and R. C. Jordan. 1960. The interrelationship and characteristic distribution of direct, diffuse, and total solar radiation. Solar Energy 4:1-19.

Lof, G. O. G., J. A. Duffie and C. O. Smith. 1966. World distribution of solar radiation. University of Wisconsin. Engineering Experiment Station Report No. 21.

Loomis, R. M. 1977. Jack pine and aspen forest floors in northeastern Minnesota. United States Department of Agriculture. Forest Service Research Note NC-222.

Loomis, R. S., W. A. Williams and W. G. Duncan. 1967. Community architecture and the productivity of terrestrial plant communities. pp. 291-308. IN A. Sam Pietro, F. A. Greer and T. J. Army (eds). Harvesting the sun. Academic Press. New York.

Lowry, G. L. 1975. Black spruce site quality as related to soil and other site conditions. Soil Science Society of America Proceedings 39:125-131.

Lowry, W. P. 1980. Clear-sky direct-beam solar radiation versus altitude. A proposal for standard soundings. Journal of Applied Meterology 19:1323-1327.

Luxmoore, R. A. Environmental Sciences Division. Oak Ridge National Laboratory. Oak Ridge, Tennessee.

Mader, D. L. 1953. Physical and chemical characteristics of the major types of forest humus found in the United States and Canada. Soil Science Society of America Proceedings 32:155-158.

Mann, L. K. and W. M. Post. 1980. Modeling the effect of drought on forest growth and composition. Bulletin of the Ecological Society of America 61:80.

McArthur, L. J. B. and J. E. Hay. 1981. A technique for mapping the distribution of diffuse solar radiation over the sky hemisphere. Journal of Applied Meterology 20:421-429.

McCaughey, J. H. 1982. Spatial variability of net radiation and soil heat flux density on two logged sites at Montmorency, Quebec. Journal of Applied Meterology 21:777-787.

Mead, D. A. 1978. Comparative height growth of eastern larch and black spruce in northwestern Ontario. Forestry Chronicles 54:296-297.

Mielke, D. L., H. H. Shugart and D. C. West. 1978. A stand model for upland forests of southern Arkansas. ORNL/TM-6225. Oak Ridge National Laboratory. Oak Ridge, Tennessee.

National Oceanic and Atmospheric Administration (NOAA). 1970-1980. Climatological data: Annual summary. Alaska. National Climatic Center. Asheville, North Carolina. vol. 56-68.

National Oceanic and Atmospheric Administration (NOAA). 1977. Local climatological data: Annual summary with comparative data. Fairbanks, Alaska. National Climatic Center. Asheville, North Carolina.

Page, G. 1976. Quantitative evaluation of site potential for spruce and fir in Newfoundland. Forest Science 22:131-143.

Page, J. K. 1961. The estimation of monthly mean values of daily total short-wave radiation on vertical and inclined surfaces from sunshine records for latitudes 40degreesN-40degreesS. Proceedings of the United Nations Conference on New Sources of Energy. Paper No. 35/5/98.

Pastor, J. and W. M. Post. 1984. Calculating Thornthwaite's AET using an approximating function. Canadian Journal of Forest Research. In Press.

Payandeh, B. 1973. Analyses of a forest drainage experiment in northern Ontario. I: Growth analysis. Canadian Journal of Forest Research 3:387-398.

Perry, T. O., H. E. Sellers and C. O. Blanchard. 1969. Estimation of photosynthetically active radiation under a forest canopy with chlorophyll extracts and from vasal area measurements. Ecology 50:39-44.

Peterson, W. A. and I. Dirmhirn. 1981. The ratio of diffuse to direct solar irradiance (perpendicular to the sun's rays) with clear skies-A conserved quantity throughout the day. Journal of Applied Meterology 20:826-828.

Piene, H. and K. Van Cleve. 1978. Weight loss of litter and cellulose bags in a thinned white spruce forest in interior Alaska. Canadian Journal of Forest Research 8:42-46.

Rieger, S., J. A. DeMent and D. Sanders (eds). 1963. Soil survey of Fairbanks area, Alaska. United States Department of Agriculture. Soil Conservation Service. Series 1959. No. 25. Washington, D.C.

Roise, J. P. and D. R. Betters. 1981. An aspect transformation with regard to elevation for site productivity models. Forest Science 27:483-486.

Salomone, L. A., W. D. Kovacs and H. Wechsler. 1982. Thermal behavior of fine-grained soils. United States Department of Commerce. National Bureau of Standards Building Science Series 149. 90 pp.

Shugart, H. H. and D. C. West. 1977. Development of an Appalachian deciduous forest succession model and its application to assessment of the impact of the chestnut blight. Journal of Environmental Management 5:161-179.

Shugart, H. H. and D. C. West. 1980. Forest succession models. Bioscience. 30:308-313.

Shugart, H. H. and I. R. Noble. 1981. A computer model of succession and fire response of the high altitude Eucalyptus forests of the Brindabella Range, Australian Capital Territory. Australian Journal of Ecology 6:149-164.

Shugart, H. H., A. T. Mortlock, M. S. Hopkins and I. P. Burgess. 1980. A computer simulation model of ecological succession in Australian subtropical rainforest. ORNL/TM-7029. Oak Ridge National Laboratory. Oak Ridge, Tennessee.

Solomon, A. M., M. L. Tharp, D. C. West, G. E. Taylor, J. W. Webb and J. C. Trimble. 1984b. Response of unmanaged forests to CO_2-induced climate change: Available information, initial tests, and data requirements. ORNL/TM. In Press. Oak Ridge National Laboratory. Oak Ridge, Tennessee.

Solomon, A. M., W. M. Post, M. L. Tharp, L. K. Mann, H. H. Shugart and D. C. West. 1984a. Development and verification of a gap model for upland forests in eastern North America. ORNL/TM. In Press. Oak Ridge National Laboratory. Oak Ridge, Tennessee.

Stage, A. R. 1976. An expression for the effect of aspect, slope and habitat type on tree growth. Forest Science 22:457-460.

Stoeckeler, E. G. 1952. Investigations of military construction in arctic and subarctic regions: Trees of interior Alaska, their significance as soil and permafrost indicators. United States Army Corps of Engineers. Saint Paul District. 25 pp.

Strang, R. M. 1973. Succession in unburned subarctic woodlands. Canadian Journal of Forest Research 3:140-143.

Swift, L. W. and K. R. Knoerr. 1973. Estimating solar radiation on mountain slopes. Agronomy Meterology 12:329-336.

Temps, R. C. and K. L. Coulson. 1977. Solar radiation incident upon slopes of different orientations. Solar Energy 19:179-184.

Thornthwaite, C. W. and J. R. Mather. 1955. The water balance. Publications in Climatology. Vol. 8. No. 1. Drexel Institute of Technology. Centerton, New Jersey.

Thornthwaite, C. W. and J. R. Mather. 1957. Instructions and tables for computing potential evapotranspiration and the water balance. Publications in Climatology. Vol. 10. No. 3. Drexel Institute of Technology. Centerton, New Jersey.

Trimble, G. R. and W. Weitzman. 1956. Aspect transformation in site productivity research. Forest Science 2:162-173.

Van Cleve, K. and C. T. Dyrness. 1979. The structure and function of a black spruce (*Picea mariana* (Mill) BSP) forest in relation to other fire affected taiga ecosystems. Progress Report and Proposed Synthesis. University of Alaska, Fairbanks.

Van Cleve, K. and C. T. Dyrness. 1978. The structure and function of a black spruce (*Picea mariana* (Mill) BSP) forest in relation to other fire affected taiga ecosystems. Progress Report and Proposed Synthesis. University of Alaska, Fairbanks.

Van Cleve, K. and C. T. Dyrness. 1983. Effects of forest-floor disturbance on soil-solution nutrient composition in a black spruce ecosystem. Canadian Journal of Forest Research 13:894-902.

Van Cleve, K. and D. Sprague. 1971. Respiration rates in the forest floor of birch and aspen stands in interior Alaska. Arctic and Alpine Research 3:17-26.

Van Cleve, K. and L. A. Viereck. 1981. Forest succession in relation to nutrient cycling in the boreal forest of Alaska. pp. 185-211. IN West, D. C., H. H. Shugart and D. B. Botkin (eds). Forest succession: Concepts and application. Springer-Verlag. New York. 517 pp.

Van Cleve, K., R. Barney and R. Schlentner. 1981. Evidence of temperature control of production and nutrient cycling in two interior Alaska black spruce ecosystems. Canadian Journal of Forest Research 11:258-273.

Viereck, L. A. 1965. Relationship of white spruce to lenses of perennially frozen ground, Mount McKinley National Park, Alaska. Arctic 18:262-267.

_________. 1970. Forest succession and soil development adjacent to the Chena River in interior Alaska. Arctic and Alpine Research 2:1-26.

_________. 1982. Effects of fire and firelines on active layer thickness and soil temperatures in interior Alaska. Proceedings Fourth Canadian Permafrost Conference. pp. 123-135.

Viereck, L. A. and C. T. Dyrness. 1979. Ecological effects of the Wickersham Dome fire near Fairbanks, Alaska. United States Department of Agriculture. Forest Service General Technical Report PNW-90.

Viereck, L. A. and C. T. Dyrness. 1979. Ecological effects of the Wickersham Dome fire near Fairbanks, Alaska. United States Department of Agriculture. Forest Service General Technical Report PNW-90. 71 pp.

Viereck, L. A. and E. L. Little. 1972. Alaska trees and shrubs. United States Department of Agriculture Forest Service. Agriculture Handbook No. 410. 265 pp.

Viereck, L. A. and L. A. Schandelmeier. 1980. Effects of fire in Alaska and adjacent Canada-A literature review. United States Department of Agriculture. Bureau of Land Management, Alaska. Technical Report 6.

Viereck, L. A., C. T. Dyrness, K. Van Cleve and M. J. Foote. 1983. Vegetation, soils and forest productivity in selected forest types in interior Alaska. Canadian Journal of Forest Research 13:703-720.

Viereck, L. A., M. J. Foote, C. T. Dyrness, K. Van Cleve, D. Kane and R. Seifert. 1979. Preliminary results of experimental fires in the black spruce type of interior Alaska. United States Department of Agriculture. Forest Service Research Note PNW-332.

Wein, R. W. and D. A. MacLean (eds). 1983. The role of fire in northern circumpolar ecosystems. John Wiley and Sons. New York.

Weinstein, D. A., H. H. Shugart and D. C. West. 1982. The long-term nutrient retention properties of forest ecosystems: A simulation investigation. ORNL/TM-8472. Oak Ridge National Laboratory. Oak Ridge, Tennessee.

Weiss, T. A. and G. O. G. Lof. 1980. The estimation of daily, clear sky, solar radiation intercepted by a tilted surface. Solar Energy 24:287-294.

Wesley, M. L. 1982. Simplified techniques to study components of solar radiation under haze and clouds. Journal of Applied Meterology 21:373-383

Wilde, G. F. and H. H. Krause. 1960. Soil-forest types of the Yukon and Tanana Valleys in subarctic Alaska. Journal of Soil Science 11:266-274.

APPENDIXES

APPENDIX A.1

SIMULATED STAND CHARACTERISTICS FOR PERMAFROST-FREE SITES BY 20-YEAR AGE INCREMENTS.
CLASS (age increment), BIOM (biomass t/ha), DENSIT (density stems/ha),
PERCENT (relative biomass)

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                                           SAS

VARIABLE          N          MEAN           STANDARD          MINIMUM          MAXIMUM
                                            DEVIATION          VALUE            VALUE

---------------------- CLASS=1   NAME=BETULA PAPYRIFERA ----------------------

BIOM            168       20.41859184      13.87595294       0.00000000      49.35252380
DENSIT          168     1509.28571429     420.12357952       0.00000000    2760.00000000
PERCENT         167       65.41501893       8.38512720      48.31253640      80.93404787

----------------------- CLASS=1   NAME=PICEA GLAUCA -----------------------

BIOM            168        5.38132532       4.28846196       0.00000000      15.01452541
DENSIT          168     1779.92857143     310.14973342       0.00000000    2448.00000000
PERCENT         167       15.66703509       4.48771738       8.80215308      27.76332237

----------------------- CLASS=1   NAME=PICEA MARIANA -----------------------

BIOM            168                 0                0                0                0
DENSIT          168                 0                0                0                0
PERCENT         167                 0                0                0                0

--------------------- CLASS=1   NAME=POPULUS TREMULOIDES ---------------------

BIOM            168        4.16884496       2.60413488       0.00000000      10.37317181
DENSIT          168     1555.14285714     685.83898781       0.00000000    2700.00000000
PERCENT         167       18.91797018       9.90295122       1.03280573      39.54824670

---------------------- CLASS=2   NAME=BETULA PAPYRIFERA ----------------------

BIOM            152       54.47140322       7.64612917      36.75465393      69.47052002
DENSIT          152      790.42105263     214.28762395     432.00000000    1392.00000000
PERCENT         152       73.53334109       5.04239766      63.48537897      81.99833269
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                                          SAS

VARIABLE             N        MEAN        STANDARD        MINIMUM        MAXIMUM
                                          DEVIATION        VALUE          VALUE

------------------------ CLASS=2   NAME=PICEA GLAUCA -----------------------

BIOM               152     19.28308352     4.06939055    10.95130730    29.58999634
DENSIT             152   1159.89473684   174.41729507   768.00000000  1584.00000000
PERCENT            152     26.13465224     5.00178822    17.43108429    36.51463986

------------------------ CLASS=2   NAME=PICEA MARIANA ----------------------

BIOM               152               0              0              0              0
DENSIT             152               0              0              0              0
PERCENT            152               0              0              0              0

--------------------- CLASS=2   NAME=POPULUS TREMULOIDES ---------------------

BIOM               152      0.20305178     0.49766779              0     2.75233078
DENSIT             152     32.44736842    75.66611824              0   396.00000000
PERCENT            152      0.33204268     0.84633461              0     4.95194158

---------------------- CLASS=3   NAME=BETULA PAPYRIFERA ----------------------

BIOM               121     56.56326080     7.45307005    38.55323792    70.45516968
DENSIT             121    388.16528926   119.73681884   156.00000000   708.00000000
PERCENT            121     68.95785423     6.81319143    51.02252028    79.80317452

------------------------ CLASS=3   NAME=PICEA GLAUCA -----------------------

BIOM               121     25.27119294     5.06135414    16.98062134    37.60931396
DENSIT             121    708.59504132   130.92151456   492.00000000  1044.00000000
PERCENT            121     31.04216226     6.81319302    20.19682548    48.97745952
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                                   SAS

VARIABLE          N         MEAN         STANDARD          MINIMUM          MAXIMUM
                                         DEVIATION          VALUE            VALUE

----------------------- CLASS=3   NAME=PICEA MARIANA -----------------------

BIOM             121             0                0                0                0
DENSIT           121             0                0                0                0
PERCENT          121             0                0                0                0

-------------------- CLASS=3   NAME=POPULUS TREMULOIDES --------------------

BIOM             121             0                0                0                0
DENSIT           121             0                0                0                0
PERCENT          121             0                0                0                0

--------------------- CLASS=4   NAME=BETULA PAPYRIFERA ---------------------

BIOM             113   47.89866341       9.23676152      26.24771118      63.39575195
DENSIT           113  189.45132743      57.84971156      84.00000000     324.00000000
PERCENT          113   61.41270171       8.60204918      39.77135580      73.84664671

----------------------- CLASS=4   NAME=PICEA GLAUCA -----------------------

BIOM             113   29.66057499       5.81802881      20.59851074      41.45916748
DENSIT           113  456.74336283      84.61433292     312.00000000     684.00000000
PERCENT          113   38.58731755       8.60205016      26.15337215      60.22864420

----------------------- CLASS=4   NAME=PICEA MARIANA -----------------------

BIOM             113             0                0                0                0
DENSIT           113             0                0                0                0
PERCENT          113             0                0                0                0
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                                          SAS

VARIABLE          N          MEAN          STANDARD          MINIMUM          MAXIMUM
                                           DEVIATION          VALUE            VALUE

---------------------- CLASS=4    NAME=POPULUS TREMULOIDES ----------------------

BIOM            113             0               0                0                0
DENSIT          113             0               0                0                0
PERCENT         113             0               0                0                0

----------------------- CLASS=5   NAME=BETULA PAPYRIFERA -----------------------

BIOM            100   38.73825134      8.83477832      22.54035950      57.04840088
DENSIT          100  100.32000000     32.91951618      48.00000000     192.00000000
PERCENT         100   53.64438167     10.25389594      34.42869344      71.93133638

------------------------- CLASS=5   NAME=PICEA GLAUCA -------------------------

BIOM            100   33.22410309      7.59912618      22.26113892      50.46630859
DENSIT          100  278.04000000     51.25494211     192.00000000     408.00000000
PERCENT         100   46.35563903     10.25389880      28.06868286      65.57132638

------------------------- CLASS=5   NAME=PICEA MARIANA -------------------------

BIOM            100             0               0                0                0
DENSIT          100             0               0                0                0
PERCENT         100             0               0                0                0

---------------------- CLASS=5    NAME=POPULUS TREMULOIDES ----------------------

BIOM            100             0               0                0                0
DENSIT          100             0               0                0                0
PERCENT         100             0               0                0                0
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                                                 SAS

VARIABLE              N          MEAN          STANDARD           MINIMUM             MAXIMUM
                                               DEVIATION           VALUE               VALUE

----------------------- CLASS=6   NAME=BETULA PAPYRIFERA ------------------------

BIOM                 86      24.46657169       9.53362195        8.82624149         43.67744446
DENSIT               86      47.16279070      19.46209617       12.00000000         96.00000000
PERCENT              86      38.47847452      12.40498124       14.73811251         62.09466858

------------------------- CLASS=6   NAME=PICEA GLAUCA ------------------------

BIOM                 86      37.91048822       7.98385978       26.59403992         57.18977356
DENSIT               86     180.27906977      37.45197746      108.00000000        276.00000000
PERCENT              86      61.52154646      12.40498029       37.90535311         85.26189518

------------------------- CLASS=6   NAME=PICEA MARIANA ------------------------

BIOM                 86                0                0                 0                   0
DENSIT               86                0                0                 0                   0
PERCENT              86                0                0                 0                   0

---------------------- CLASS=6   NAME=POPULUS TREMULOIDES ---------------------

BIOM                 86                0                0                 0                   0
DENSIT               86                0                0                 0                   0
PERCENT              86                0                0                 0                   0

----------------------- CLASS=7   NAME=BETULA PAPYRIFERA ------------------------

BIOM                 60       9.88231821       5.72151267                 0         18.29039001
DENSIT               60      14.40000000       8.49965104                 0         24.00000000
PERCENT              60      19.64002222      10.79502937                 0         37.63183696
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                                          SAS

VARIABLE          N          MEAN        STANDARD         MINIMUM         MAXIMUM
                                         DEVIATION        VALUE           VALUE

-------------------------- CLASS=7    NAME=PICEA GLAUCA --------------------------

BIOM             60    38.80920970      4.87289197     30.31309509     50.04293823
DENSIT           60   100.80000000     19.78597346     72.00000000    168.00000000
PERCENT          60    80.35999607     10.79501818     62.36813165    100.00000000

-------------------------- CLASS=7    NAME=PICEA MARIANA --------------------------

BIOM             60              0               0               0               0
DENSIT           60              0               0               0               0
PERCENT          60              0               0               0               0

---------------------- CLASS=7    NAME=POPULUS TREMULOIDES ----------------------

BIOM             60              0               0               0               0
DENSIT           60              0               0               0               0
PERCENT          60              0               0               0               0

------------------------ CLASS=8    NAME=BETULA PAPYRIFERA ------------------------

BIOM             32     2.99654341      7.07671755               0     19.76535034
DENSIT           32     3.75000000      8.85364878               0     24.00000000
PERCENT          32     5.79280738     13.67703870               0     37.43155548

-------------------------- CLASS=8    NAME=PICEA GLAUCA --------------------------

BIOM             32    35.74468279      9.43478462     21.35531616     53.28617859
DENSIT           32    63.37500000     18.59890736     36.00000000     96.00000000
PERCENT          32    94.20719895     13.67702385     62.56844452    100.00000000
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                                          SAS

VARIABLE          N        MEAN         STANDARD          MINIMUM          MAXIMUM
                                        DEVIATION          VALUE            VALUE

------------------------ CLASS=8   NAME=PICEA MARIANA ------------------------

BIOM             32              0              0                0                0
DENSIT           32              0              0                0                0
PERCENT          32              0              0                0                0

--------------------- CLASS=8   NAME=POPULUS TREMULOIDES ---------------------

BIOM             32              0              0                0                0
DENSIT           32              0              0                0                0
PERCENT          32              0              0                0                0

---------------------- CLASS=9   NAME=BETULA PAPYRIFERA ----------------------

BIOM             20              0              0                0                0
DENSIT           20              0              0                0                0
PERCENT          20              0              0                0                0

------------------------ CLASS=9   NAME=PICEA GLAUCA -------------------------

BIOM             20    28.90093689     3.33276061      23.61840820      34.34173584
DENSIT           20    36.00000000     0.00000000      36.00000000      36.00000000
PERCENT          20   100.00000000     0.00000000     100.00000000     100.00000000

------------------------ CLASS=9   NAME=PICEA MARIANA ------------------------

BIOM             20              0              0                0                0
DENSIT           20              0              0                0                0
PERCENT          20              0              0                0                0
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                                          SAS

VARIABLE              N          MEAN          STANDARD          MINIMUM          MAXIMUM
                                               DEVIATION          VALUE            VALUE

---------------------- CLASS=9    NAME=POPULUS TREMULOIDES ---------------------

BIOM                 20              0              0               0                0
DENSIT               20              0              0               0                0
PERCENT              20              0              0               0                0

---------------------- CLASS=10    NAME=BETULA PAPYRIFERA ----------------------

BIOM                 20              0              0               0                0
DENSIT               20              0              0               0                0
PERCENT              20              0              0               0                0

------------------------- CLASS=10    NAME=PICEA GLAUCA ------------------------

BIOM                 20     28.59122009     3.67091507     18.25851440      35.47895813
DENSIT               20     24.60000000     4.72841355     12.00000000      36.00000000
PERCENT              20    100.00000000     0.00000000    100.00000000     100.00000000

------------------------ CLASS=10    NAME=PICEA MARIANA ------------------------

BIOM                 20              0              0               0                0
DENSIT               20              0              0               0                0
PERCENT              20              0              0               0                0

--------------------- CLASS=10    NAME=POPULUS TREMULOIDES ---------------------

BIOM                 20              0              0               0                0
DENSIT               20              0              0               0                0
PERCENT              20              0              0               0                0
```

APPENDIX A.2

REPORTED STAND CHARACTERISTICS FOR PERMAFROST-FREE SITES BY 20-YEAR AGE INCREMENTS.
CLASS (age increment), BIOM (biomass t/ha), DENSIT (density stems/ha),
PERCENT (relative biomass)

```
                                         SAS

VARIABLE        N       MEAN          STANDARD        MINIMUM        MAXIMUM
                                      DEVIATION       VALUE          VALUE

--------------------- CLASS=1   NAME=BETULA PAPYRIFERA ---------------------

BIOM           157    0.52161840     2.11989743              0     20.14903018
DENSIT         157   16.89827451    54.98922299              0    348.88804148
PERCENT        107   11.51769742    25.82415993              0     92.85243880

---------------------- CLASS=1   NAME=LARIX LARICINA -----------------------

BIOM           157    0.02685526     0.29608673              0      3.69781811
DENSIT         157   16.80075152   195.75668143              0   2451.98364972
PERCENT        107    0.96794269     8.43612023              0     86.83313689

----------------------- CLASS=1   NAME=PICEA GLAUCA ------------------------

BIOM           157    1.83914812     9.11505052              0     96.01762080
DENSIT         157   39.51408467   156.36841482              0   1426.02241351
PERCENT        107   11.01674992    26.84865977              0     99.03630907

----------------------- CLASS=1   NAME=PICEA MARIANA -----------------------

BIOM           157    2.36795522     4.71676433     0.00000000     25.17436927
DENSIT         157  499.69728961   910.54990531     0.00000000   5194.38357276
PERCENT        107   64.34345967    40.70197996     0.09216158    100.00000000

-------------------- CLASS=1   NAME=POPULUS BALSAMIFERA --------------------

BIOM           157    0.00297722     0.03730450              0      0.46742407
DENSIT         157    0.03756530     0.47069190              0      5.89775258
PERCENT        107    0.00439609     0.04547354              0      0.47038196
```

```
                                        SAS

VARIABLE          N         MEAN          STANDARD          MINIMUM         MAXIMUM
                                          DEVIATION         VALUE           VALUE

---------------------- CLASS=1   NAME=POPULUS TREMULOIDES ----------------------

BIOM            157       2.14896415     11.99461466              0     95.19971444
DENSIT          157      78.56530669    417.98188539              0   4031.87301722
PERCENT         107      12.14975422     27.64768094              0     98.90470535

---------------------- CLASS=2   NAME=BETULA PAPYRIFERA ----------------------

BIOM              3       0.36676232      0.63525097              0      1.10028696
DENSIT            3      12.14149946     21.02969395              0     36.42449839
PERCENT           3       1.07463354      1.86131990              0      3.22390063

---------------------- CLASS=2   NAME=LARIX LARICINA ----------------------

BIOM              3       0.00572706      0.00991955              0      0.01718117
DENSIT            3       9.90883868     17.16261204              0     29.72651605
PERCENT           3       0.06323816      0.10953171              0      0.18971448

---------------------- CLASS=2   NAME=PICEA GLAUCA ----------------------

BIOM              3       1.84306746      3.05799378     0.01239417      5.37332331
DENSIT            3     207.81802844    284.86031243    15.52779961    535.07728894
PERCENT           3      20.12429743     33.95522997     0.42041855     59.33225006

---------------------- CLASS=2   NAME=PICEA MARIANA ----------------------

BIOM              3       2.63554174      0.90232437     1.98594444      3.66582375
DENSIT            3     640.63549714     45.50767539   605.58418494    692.06546939
PERCENT           3      48.82155515     46.94586812     6.60685369     99.37977631
```

```
                                          SAS

VARIABLE          N          MEAN           STANDARD           MINIMUM          MAXIMUM
                                            DEVIATION           VALUE            VALUE

--------------------- CLASS=2   NAME=POPULUS BALSAMIFERA ---------------------

BIOM              3              0               0                 0                0
DENSIT            3              0               0                 0                0
PERCENT           3              0               0                 0                0

--------------------- CLASS=2   NAME=POPULUS TREMULOIDES ---------------------

BIOM              3    10.21014351     17.68448732                 0      30.63043054
DENSIT            3   704.20696886   1219.72224910                 0    2112.62090657
PERCENT           3    29.91627571     51.81650950                 0      89.74882713

---------------------- CLASS=3   NAME=BETULA PAPYRIFERA ----------------------

BIOM             25     3.72801220      9.78777299                 0      37.81768361
DENSIT           25   118.40755764    267.62795492                 0    1319.08719166
PERCENT          25    11.40196998     23.67868651                 0      82.86302196

----------------------- CLASS=3   NAME=LARIX LARICINA -----------------------

BIOM             25     0.10090325      0.50451626                 0       2.52258132
DENSIT           25     7.61195866     38.05979329                 0     190.29896647
PERCENT          25     0.60386891      3.01934457                 0      15.09672285

------------------------ CLASS=3   NAME=PICEA GLAUCA ------------------------

BIOM             25     1.39711435      2.63773746                 0      11.93211674
DENSIT           25    57.70666859     70.52888739                 0     217.48453311
PERCENT          25    11.19428000     23.41073069                 0      96.16987499
```

```
                                          SAS

VARIABLE           N         MEAN        STANDARD           MINIMUM         MAXIMUM
                                         DEVIATION           VALUE           VALUE

------------------------ CLASS=3   NAME=PICEA MARIANA ------------------------

BIOM              25     7.96499024     9.03087637      0.04560175     44.59298358
DENSIT            25  1626.63472829  1477.44289599     19.52711818   4988.44780508
PERCENT           25    63.26863327    38.29025985      0.47830781    100.00000000

--------------------- CLASS=3   NAME=POPULUS BALSAMIFERA ---------------------

BIOM              25     0.00480888     0.02404441               0      0.12022204
DENSIT            25     3.14384655    15.71923273               0     78.59616366
PERCENT           25     0.01087184     0.05435920               0      0.27179602

--------------------- CLASS=3   NAME=POPULUS TREMULOIDES ---------------------

BIOM              25     8.48296767    22.67166586               0    102.01610373
DENSIT            25   247.57369488   593.91638091               0   2515.07723706
PERCENT           25    13.52037599    29.50860167               0     94.40419638

---------------------- CLASS=4   NAME=BETULA PAPYRIFERA ----------------------

BIOM              11     0.31627913     0.57509619               0      1.63432925
DENSIT            11    58.17830051   109.64702156               0    280.05321011
PERCENT           11     1.16123428     2.05031844               0      5.54413362

------------------------ CLASS=4   NAME=LARIX LARICINA ------------------------

BIOM              11     0.35268163     1.16971264               0      3.87949795
DENSIT            11   199.36172918   661.20805326               0   2192.97902102
PERCENT           11     8.55763670    28.38247004               0     94.13400373
```

```
                                          SAS

VARIABLE           N         MEAN           STANDARD          MINIMUM          MAXIMUM
                                            DEVIATION           VALUE            VALUE

------------------------- CLASS=4    NAME=PICEA GLAUCA --------------------------

BIOM              11      0.30421649      0.65570763                0       1.67685652
DENSIT            11     21.70836264     43.54300855                0     132.19644392
PERCENT           11     13.08743199     28.87660908                0      89.02820973

------------------------- CLASS=4    NAME=PICEA MARIANA -------------------------

BIOM              11     15.39635856     12.55324221       0.01097982      31.15314455
DENSIT            11   2217.66916102   1860.30252589      13.32479362    5694.41527224
PERCENT           11     73.72709586     35.94208815       5.86599627     100.00000000

---------------------- CLASS=4    NAME=POPULUS BALSAMIFERA ----------------------

BIOM              11               0               0                0                0
DENSIT            11               0               0                0                0
PERCENT           11               0               0                0                0

---------------------- CLASS=4    NAME=POPULUS TREMULOIDES ----------------------

BIOM              11      0.60717668      1.81790517                0       6.05966914
DENSIT            11     38.80520384    113.76864341                0     379.09963836
PERCENT           11      3.46660116     10.80766349                0      35.99554709

----------------------- CLASS=5    NAME=BETULA PAPYRIFERA -----------------------

BIOM               2      0.88267465      1.24829046                0       1.76534930
DENSIT             2     29.22054204     41.32408685                0      58.44108408
PERCENT            2      2.29952469      3.25201900                0       4.59904938
```

```
                                          SAS

VARIABLE          N          MEAN          STANDARD          MINIMUM          MAXIMUM
                                           DEVIATION           VALUE            VALUE

----------------------- CLASS=5   NAME=LARIX LARICINA -----------------------

BIOM              2               0               0               0               0
DENSIT            2               0               0               0               0
PERCENT           2               0               0               0               0

------------------------ CLASS=5   NAME=PICEA GLAUCA ------------------------

BIOM              2      0.60803123      0.85988601               0      1.21606245
DENSIT            2    146.10271021    206.62043427               0    292.20542041
PERCENT           2      1.58402965      2.24015621               0      3.16805929

------------------------ CLASS=5   NAME=PICEA MARIANA -----------------------

BIOM              2     16.26987180     20.47882740      1.78915407     30.75058953
DENSIT            2   2533.87188907   2367.23251618    859.98572424   4207.75805391
PERCENT           2     90.05538154     14.06381429     80.11076309    100.00000000

--------------------- CLASS=5   NAME=POPULUS BALSAMIFERA --------------------

BIOM              2      2.32654499      3.29023148               0      4.65308999
DENSIT            2     58.44108408     82.64817371               0    116.88216816
PERCENT           2      6.06106412      8.57163908               0     12.12212824

--------------------- CLASS=5   NAME=POPULUS TREMULOIDES --------------------

BIOM              2               0               0               0               0
DENSIT            2               0               0               0               0
PERCENT           2               0               0               0               0
```

```
                                        SAS

VARIABLE              N          MEAN         STANDARD         MINIMUM          MAXIMUM
                                              DEVIATION         VALUE            VALUE

----------------------- CLASS=6    NAME=BETULA PAPYRIFERA ----------------------

BIOM                  6      0.75644979      1.19713733              0       2.65606209
DENSIT                6     45.94435462     95.14117744              0     237.65443825
PERCENT               6      5.32306340     11.49500362              0      28.63124955

------------------------ CLASS=6    NAME=LARIX LARICINA -----------------------

BIOM                  6      0.05148951      0.12612303              0       0.30893707
DENSIT                6      4.16937611     10.21284401              0      25.01625666
PERCENT               6      0.78305553      1.91808650              0       4.69833320

------------------------- CLASS=6    NAME=PICEA GLAUCA ------------------------

BIOM                  6      7.39290752     16.96916833              0      41.97647988
DENSIT                6    102.99388064    165.77896235              0     380.11689474
PERCENT               6     23.87740308     38.96579398              0      90.99842939

------------------------- CLASS=6    NAME=PICEA MARIANA -----------------------

BIOM                  6      9.29833223     13.56143364     0.23552524      35.68064180
DENSIT                6    998.42962256   1010.13282581    38.47515118    2762.80777247
PERCENT               6     70.01647798     37.64539107     9.00157061     100.00000000

---------------------- CLASS=6    NAME=POPULUS BALSAMIFERA ---------------------

BIOM                  6               0               0              0                0
DENSIT                6               0               0              0                0
PERCENT               6               0               0              0                0
```

```
                                        SAS

VARIABLE          N          MEAN          STANDARD            MINIMUM          MAXIMUM
                                           DEVIATION            VALUE            VALUE

-------------------- CLASS=6   NAME=POPULUS TREMULOIDES --------------------

BIOM              6                0              0                  0                0
DENSIT            6                0              0                  0                0
PERCENT           6                0              0                  0                0

--------------------- CLASS=7   NAME=BETULA PAPYRIFERA ---------------------

BIOM              8       3.14595760     4.59587061                  0      11.99166078
DENSIT            8      54.57966662    91.50197110                  0     270.21081933
PERCENT           8       4.70918686     6.30265315                  0      15.45650601

---------------------- CLASS=7   NAME=LARIX LARICINA -----------------------

BIOM              8       0.05242114     0.14826939                  0       0.41936916
DENSIT            8      25.33669655    71.66299976                  0     202.69357236
PERCENT           8       0.31879244     0.90168118                  0       2.55033951

----------------------- CLASS=7   NAME=PICEA GLAUCA ------------------------

BIOM              8       1.27391609     3.60317884                  0      10.19132876
DENSIT            8       9.78357748    27.67213593                  0      78.26861986
PERCENT           8       1.78844760     5.05849370                  0      14.30758079

----------------------- CLASS=7   NAME=PICEA MARIANA -----------------------

BIOM              8      23.80421341    20.59201127         3.69719826      59.94109725
DENSIT            8    1694.13753771   882.72952103       709.30340073    3445.79073015
PERCENT           8      82.45211184    32.67743345         3.33415621     100.00000000
```

```
                                          SAS

VARIABLE              N          MEAN          STANDARD           MINIMUM          MAXIMUM
                                               DEVIATION           VALUE            VALUE

--------------------- CLASS=7   NAME=POPULUS BALSAMIFERA --------------------

BIOM                  8               0               0               0                0
DENSIT                8               0               0               0                0
PERCENT               8               0               0               0                0

--------------------- CLASS=7   NAME=POPULUS TREMULOIDES --------------------

BIOM                  8     11.89996430     33.65818182               0      95.19971444
DENSIT                8    215.32424665    609.02893984               0    1722.59397320
PERCENT               8     10.73146126     30.35315612               0      85.85169008

---------------------- CLASS=8   NAME=BETULA PAPYRIFERA ---------------------

BIOM                 12      1.79332383      3.27815529               0       8.73453299
DENSIT               12     41.46068983     76.21473347               0     246.36579654
PERCENT              12      3.58937769      7.03290053               0      21.87619620

----------------------- CLASS=8   NAME=LARIX LARICINA -----------------------

BIOM                 12      0.25448789      0.88157192               0       3.05385473
DENSIT               12      2.51845175      8.72417278               0      30.22142102
PERCENT              12      0.17573480      0.60876322               0       2.10881765

------------------------ CLASS=8   NAME=PICEA GLAUCA ------------------------

BIOM                 12      0.62430986      2.16267278               0       7.49171826
DENSIT               12     22.66606576     78.51755502               0     271.99278917
PERCENT              12      0.43111273      1.49341830               0       5.17335273
```

```
                                              SAS

VARIABLE              N          MEAN         STANDARD          MINIMUM           MAXIMUM
                                              DEVIATION           VALUE             VALUE

------------------------- CLASS=8   NAME=PICEA MARIANA -------------------------

BIOM                 12     34.54004128     36.15999299       3.07350726     134.26802576
DENSIT               12   2023.54423705   1196.13199160     493.82716049    4596.38035047
PERCENT              12     95.80377478      7.00916612      78.12380380     100.00000000

---------------------- CLASS=8   NAME=POPULUS BALSAMIFERA ----------------------

BIOM                 12               0               0                0                0
DENSIT               12               0               0                0                0
PERCENT              12               0               0                0                0

---------------------- CLASS=8   NAME=POPULUS TREMULOIDES ----------------------

BIOM                 12               0               0                0                0
DENSIT               12               0               0                0                0
PERCENT              12               0               0                0                0

----------------------- CLASS=9   NAME=BETULA PAPYRIFERA -----------------------

BIOM                  1               0               .                0                0
DENSIT                1               0               .                0                0
PERCENT               1               0               .                0                0

------------------------ CLASS=9   NAME=LARIX LARICINA -------------------------

BIOM                  1               0               .                0                0
DENSIT                1               0               .                0                0
PERCENT               1               0               .                0                0
```

```
                                         SAS
VARIABLE          N         MEAN        STANDARD          MINIMUM         MAXIMUM
                                        DEVIATION          VALUE           VALUE

------------------------ CLASS=9   NAME=PICEA GLAUCA -------------------------

BIOM              1            0             .                 0               0
DENSIT            1            0             .                 0               0
PERCENT           1            0             .                 0               0

------------------------ CLASS=9   NAME=PICEA MARIANA --------------------------

BIOM              1   3.78905989             .        3.78905989      3.78905989
DENSIT            1 1423.99430402            .     1423.99430402   1423.99430402
PERCENT           1  100.00000000            .      100.00000000    100.00000000

--------------------- CLASS=9   NAME=POPULUS BALSAMIFERA ---------------------

BIOM              1            0             .                 0               0
DENSIT            1            0             .                 0               0
PERCENT           1            0             .                 0               0

--------------------- CLASS=9   NAME=POPULUS TREMULOIDES ---------------------

BIOM              1            0             .                 0               0
DENSIT            1            0             .                 0               0
PERCENT           1            0             .                 0               0

--------------------- CLASS=10   NAME=BETULA PAPYRIFERA ----------------------

BIOM              2   3.58470050    5.06953207                 0      7.16940101
DENSIT            2  64.00389144   90.51517131                 0    128.00778287
PERCENT           2   2.70464512    3.82494581                 0      5.40929025
```

```
                                        SAS

VARIABLE           N        MEAN        STANDARD       MINIMUM        MAXIMUM
                                        DEVIATION      VALUE          VALUE

---------------------- CLASS=10   NAME=LARIX LARICINA ----------------------

BIOM               2              0            0              0              0
DENSIT             2              0            0              0              0
PERCENT            2              0            0              0              0

---------------------- CLASS=10   NAME=PICEA GLAUCA -----------------------

BIOM               2    25.52876604   9.36623180    18.90584002    32.15169206
DENSIT             2   342.48368999 393.82990796    64.00389144   620.96348854
PERCENT            2    57.07372220  60.54152953    14.26439613    99.88304828

---------------------- CLASS=10   NAME=PICEA MARIANA ----------------------

BIOM               2    53.25053435  75.25438841     0.03764599   106.46342271
DENSIT             2   551.99414758 758.12030249    15.92214073  1088.06615442
PERCENT            2    40.22163268  56.71658372     0.11695172    80.32631363

------------------- CLASS=10   NAME=POPULUS BALSAMIFERA --------------------

BIOM               2              0            0              0              0
DENSIT             2              0            0              0              0
PERCENT            2              0            0              0              0

------------------- CLASS=10   NAME=POPULUS TREMULOIDES --------------------

BIOM               2              0            0              0              0
DENSIT             2              0            0              0              0
PERCENT            2              0            0              0              0
```

APPENDIX A.3

SIMULATED STAND CHARACTERISTICS FOR PERMAFROST SITES WITH SHALLOW SPECIES' ACTIVE LAYER DEPTH REQUIREMENTS BY 20-YEAR AGE INCREMENTS. CLASS (age increment), BIOM (biomass t/ha), DENSIT (density stems/ha), PERCENT (relative biomass)

```
                                        SAS

VARIABLE          N          MEAN          STANDARD        MINIMUM          MAXIMUM
                                           DEVIATION         VALUE            VALUE

----------------------- CLASS=1   NAME=BETULA PAPYRIFERA -----------------------

BIOM             168      8.10487074      6.76934051              0      22.87300110
DENSIT           168    992.71428571    391.87003135              0    2136.00000000
PERCENT          167     74.08776864     23.01865082              0      94.14782052

------------------------- CLASS=1   NAME=PICEA GLAUCA -------------------------

BIOM             168      0.72907083      0.87041641     0.00000000       3.69964314
DENSIT           168   1323.42857143    371.72323378     0.00000000    2340.00000000
PERCENT          167      7.67664095      4.03688603     0.95322645      16.50300808

------------------------- CLASS=1   NAME=PICEA MARIANA -------------------------

BIOM             168      0.67547924      0.38474961     0.00000000       1.59199047
DENSIT           168   1523.28571429    314.00745906     0.00000000    2292.00000000
PERCENT          167     13.88728746     19.72201392     4.67125114      92.59540710

---------------------- CLASS=1   NAME=POPULUS TREMULOIDES ----------------------

BIOM             168      0.13668354      0.21119444              0       0.81779814
DENSIT           168    387.92857143    590.97523755              0    2508.00000000
PERCENT          167      4.34833659      7.66586957              0      31.89910568

----------------------- CLASS=2   NAME=BETULA PAPYRIFERA -----------------------

BIOM             152     24.33964953     10.37498021              0      39.23559570
DENSIT           152    467.13157895    228.85000971              0    1080.00000000
PERCENT          152     74.81059319     29.50756807              0      95.62028871
```

```
                                        SAS

VARIABLE           N         MEAN         STANDARD        MINIMUM        MAXIMUM
                                          DEVIATION         VALUE          VALUE

------------------------- CLASS=2   NAME=PICEA GLAUCA ------------------------

BIOM             152     2.94760169     2.46518655     0.04260304     8.58962822
DENSIT           152   799.50000000   221.61708520   384.00000000  1476.00000000
PERCENT          152     8.67546615     5.70364185     0.34117736    17.91565097

------------------------- CLASS=2   NAME=PICEA MARIANA -----------------------

BIOM             152     1.44566988     0.50520120     0.74600887     3.30019283
DENSIT           152  1003.57894737   245.13714303   600.00000000  1644.00000000
PERCENT          152    16.50974076    31.41828055     1.60988708    98.72562602

---------------------- CLASS=2   NAME=POPULUS TREMULOIDES --------------------

BIOM             152     0.00130947     0.00935960              0     0.07321417
DENSIT           152     0.86842105     6.19194543              0    48.00000000
PERCENT          152     0.00420613     0.03021609              0     0.24456808

----------------------- CLASS=3   NAME=BETULA PAPYRIFERA ---------------------

BIOM             121    28.03687885    13.16162156              0    42.01782227
DENSIT           121   235.93388430   121.04102166              0   456.00000000
PERCENT          121    72.83300822    33.04082434              0    97.37810994

------------------------- CLASS=3   NAME=PICEA GLAUCA ------------------------

BIOM             121     3.63386277     3.19603930     0.01708793     8.99247169
DENSIT           121   439.23966942   105.78256195   228.00000000   636.00000000
PERCENT          121     8.86207138     7.49723900     0.27529847    25.98763193
```

```
                                         SAS

VARIABLE           N          MEAN          STANDARD        MINIMUM         MAXIMUM
                                            DEVIATION        VALUE           VALUE

--------------------- CLASS=3   NAME=PICEA MARIANA -----------------------

BIOM              121       1.45491328      1.50084153      0.32146025      6.18996811
DENSIT            121     549.02479339    203.94870527    312.00000000   1104.00000000
PERCENT           121      18.30493063     36.21366890      0.91745990     99.72473208

------------------- CLASS=3   NAME=POPULUS TREMULOIDES -------------------

BIOM              121                0               0               0               0
DENSIT            121                0               0               0               0
PERCENT           121                0               0               0               0

-------------------- CLASS=4   NAME=BETULA PAPYRIFERA --------------------

BIOM              113      24.45895980     12.58014392               0     41.10997009
DENSIT            113     126.26548673     72.73017866               0    264.00000000
PERCENT           113      71.26361804     34.50660184               0     98.10671444

--------------------- CLASS=4   NAME=PICEA GLAUCA ------------------------

BIOM              113       3.50946347      3.68951200      0.01069271     10.83994389
DENSIT            113     233.30973451     84.12141307     84.00000000    420.00000000
PERCENT           113       9.91143178     10.99240678      0.12509232     37.96665242

--------------------- CLASS=4   NAME=PICEA MARIANA -----------------------

BIOM              113       1.69697011      2.70711719      0.10149425      8.53716660
DENSIT            113     314.54867257    190.63207791     96.00000000    828.00000000
PERCENT           113      18.82495898     37.73850693      0.35548127     99.87494250
```

```
                                              SAS

VARIABLE         N         MEAN          STANDARD         MINIMUM          MAXIMUM
                                         DEVIATION         VALUE            VALUE

---------------------- CLASS=4   NAME=POPULUS TREMULOIDES ---------------------

BIOM            113              0               0               0                0
DENSIT          113              0               0               0                0
PERCENT         113              0               0               0                0

----------------------- CLASS=5   NAME=BETULA PAPYRIFERA ----------------------

BIOM            100    17.39963789      9.55496360               0      30.37509155
DENSIT          100    59.40000000     38.15280283               0     132.00000000
PERCENT         100    68.35396641     36.50295416               0      98.54679441

------------------------- CLASS=5   NAME=PICEA GLAUCA -------------------------

BIOM            100     3.02700354      4.41935665      0.00479352      13.56124878
DENSIT          100   120.72000000     55.81319492     48.00000000     228.00000000
PERCENT         100    10.34618001     14.14326390      0.05152666      38.56680334

------------------------- CLASS=5   NAME=PICEA MARIANA ------------------------

BIOM            100     2.15893525      3.62010267      0.04864497      10.01239586
DENSIT          100   189.60000000    158.82294316     48.00000000     576.00000000
PERCENT         100    21.29986412     39.52986492      0.13834131      99.94847718

---------------------- CLASS=5   NAME=POPULUS TREMULOIDES ---------------------

BIOM            100              0               0               0                0
DENSIT          100              0               0               0                0
PERCENT         100              0               0               0                0
```

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                                          SAS

VARIABLE           N         MEAN          STANDARD          MINIMUM           MAXIMUM
                                           DEVIATION          VALUE             VALUE

----------------------- CLASS=6    NAME=BETULA PAPYRIFERA ----------------------

BIOM              86    10.42270605      7.76809902                0       25.06056213
DENSIT            86    23.58139535     18.53991885                0       72.00000000
PERCENT           86    60.30499123     35.55472667                0       97.87073153

------------------------- CLASS=6    NAME=PICEA GLAUCA ------------------------

BIOM              86     3.13209879      5.03678769       0.00086331       14.83979607
DENSIT            86    68.65116279     47.98768652      12.00000000      180.00000000
PERCENT           86    12.60198238     15.78792462       0.00919199       54.78901436

------------------------- CLASS=6    NAME=PICEA MARIANA -----------------------

BIOM              86     2.59646461      3.71404804       0.04864497        9.67285633
DENSIT            86   137.02325581    108.56269284      48.00000000      396.00000000
PERCENT           86    27.09304379     40.65975189       0.12414356       99.99082067

---------------------- CLASS=6    NAME=POPULUS TREMULOIDES ---------------------

BIOM              86              0               0                0                 0
DENSIT            86              0               0                0                 0
PERCENT           86              0               0                0                 0

----------------------- CLASS=7    NAME=BETULA PAPYRIFERA ----------------------

BIOM              60     2.97521001      3.95937406                0        9.07046890
DENSIT            60     4.40000000      5.83153322                0       12.00000000
PERCENT           60    28.96965632     38.87372420                0       85.89611971
```

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                                          SAS

VARIABLE           N          MEAN         STANDARD         MINIMUM          MAXIMUM
                                           DEVIATION          VALUE            VALUE

------------------------- CLASS=7   NAME=PICEA GLAUCA -------------------------

BIOM              60    2.31975395      3.01372977               0       7.38572384
DENSIT            60   36.60000000     28.75802025               0      84.00000000
PERCENT           60   32.72913982     43.78651472               0      98.90735095

------------------------- CLASS=7   NAME=PICEA MARIANA ------------------------

BIOM              60    2.96273048      3.36413823      0.07066911       9.77337742
DENSIT            60   99.60000000     73.51955810     36.00000000     276.00000000
PERCENT           60   38.30122177     44.22208964      0.48524833     100.00000000

---------------------- CLASS=7   NAME=POPULUS TREMULOIDES ---------------------

BIOM              60             0               0               0                0
DENSIT            60             0               0               0                0
PERCENT           60             0               0               0                0

----------------------- CLASS=8   NAME=BETULA PAPYRIFERA ----------------------

BIOM              32    6.16662499      4.86496043               0      10.55426788
DENSIT            32    7.50000000      5.90243252               0      12.00000000
PERCENT           32   54.03798448     42.53203756               0      87.56265754

------------------------- CLASS=8   NAME=PICEA GLAUCA -------------------------

BIOM              32    0.81360798      1.56418303               0       4.38603973
DENSIT            32   15.00000000     15.24001524               0      48.00000000
PERCENT           32   16.02755824     34.69728298               0      95.79540079
```

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                                         SAS

VARIABLE          N          MEAN        STANDARD        MINIMUM        MAXIMUM
                                         DEVIATION        VALUE          VALUE

------------------------ CLASS=8   NAME=PICEA MARIANA -----------------------

BIOM             32     2.04261487     1.82946303     0.19251209     5.50481415
DENSIT           32    55.50000000    34.85268537    36.00000000   120.00000000
PERCENT          32    29.93446868    37.76043457     4.20465258   100.00000000

--------------------- CLASS=8   NAME=POPULUS TREMULOIDES --------------------

BIOM             32              0              0              0              0
DENSIT           32              0              0              0              0
PERCENT          32              0              0              0              0

---------------------- CLASS=9   NAME=BETULA PAPYRIFERA ---------------------

BIOM             20     2.68795161     4.77686243              0    10.88393974
DENSIT           20     3.00000000     5.33113990              0    12.00000000
PERCENT          20    21.39823696    38.02572164              0    85.78859204

------------------------ CLASS=9   NAME=PICEA GLAUCA ------------------------

BIOM             20     0.05131571     0.09119041              0     0.20526284
DENSIT           20     3.00000000     5.33113990              0    12.00000000
PERCENT          20     0.40855097     0.72606539              0     1.65789351

------------------------ CLASS=9   NAME=PICEA MARIANA -----------------------

BIOM             20     1.81989350     0.17429488     1.55424500     2.10794067
DENSIT           20    36.00000000     0.00000000    36.00000000    36.00000000
PERCENT          20    78.19321491    38.75174515    12.55352744   100.00000000
```

```
                                          SAS

VARIABLE           N          MEAN         STANDARD        MINIMUM        MAXIMUM
                                           DEVIATION        VALUE          VALUE

---------------------- CLASS=9   NAME=POPULUS TREMULOIDES ---------------------

BIOM              20              0              0              0              0
DENSIT            20              0              0              0              0
PERCENT           20              0              0              0              0

---------------------- CLASS=10   NAME=BETULA PAPYRIFERA ----------------------

BIOM              20              0              0              0              0
DENSIT            20              0              0              0              0
PERCENT           20              0              0              0              0

------------------------- CLASS=10   NAME=PICEA GLAUCA -------------------------

BIOM              20              0              0              0              0
DENSIT            20              0              0              0              0
PERCENT           20              0              0              0              0

------------------------ CLASS=10   NAME=PICEA MARIANA ------------------------

BIOM              20     2.28387856     0.06613745     2.13995552     2.34982014
DENSIT            20    36.00000000     0.00000000    36.00000000    36.00000000
PERCENT           20   100.00000000     0.00000000   100.00000000   100.00000000

--------------------- CLASS=10   NAME=POPULUS TREMULOIDES ---------------------

BIOM              20              0              0              0              0
DENSIT            20              0              0              0              0
PERCENT           20              0              0              0              0
```

APPENDIX A.4

SIMULATED STAND CHARACTERISTICS FOR PERMAFROST SITES WITH INTERMEDIATE SPECIES' ACTIVE LAYER DEPTH REQUIREMENTS BY 20-YEAR AGE INCREMENTS. CLASS (age increment), BIOM (biomass t/ha), DENSIT (density stems/ha), PERCENT (relative biomass)

```
                                        SAS

VARIABLE          N         MEAN          STANDARD          MINIMUM          MAXIMUM
                                          DEVIATION          VALUE            VALUE

----------------------- CLASS=1   NAME=BETULA PAPYRIFERA ----------------------

BIOM             168      4.05613740      3.83926355               0      17.85253906
DENSIT           168    991.71428571    420.60067031               0    2136.00000000
PERCENT          167     61.14364836     19.87088316               0      80.37433843

------------------------- CLASS=1   NAME=PICEA GLAUCA -------------------------

BIOM             168      1.01185055      1.27940604      0.00000000       5.77911472
DENSIT           168   1385.21428571    369.06115137      0.00000000    2412.00000000
PERCENT          167     13.83202873      6.10354032      3.25959641      29.52436672

------------------------- CLASS=1   NAME=PICEA MARIANA ------------------------

BIOM             168      0.71490391      0.42616170      0.00000000       1.78408146
DENSIT           168   1543.57142857    325.20351199      0.00000000    2292.00000000
PERCENT          167     19.19704183     19.62455894      6.22454790      93.60844468

--------------------- CLASS=1   NAME=POPULUS TREMULOIDES ---------------------

BIOM             168      0.19912215      0.30100785               0       1.37678146
DENSIT           168    405.78571429    568.47273217               0    2124.00000000
PERCENT          167      5.82731222      8.57894999               0      32.16941441

----------------------- CLASS=2   NAME=BETULA PAPYRIFERA ----------------------

BIOM             152     13.77011315      8.83818786               0      30.32231140
DENSIT           152    449.05263158    246.48661797               0    1152.00000000
PERCENT          152     57.02455621     23.72995605               0      79.07029728
```

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                                        SAS

VARIABLE            N        MEAN         STANDARD         MINIMUM         MAXIMUM
                                          DEVIATION        VALUE           VALUE

------------------------ CLASS=2   NAME=PICEA GLAUCA ------------------------

BIOM              152     4.85205769      3.82866463      0.04076397     12.67727375
DENSIT            152   817.89473684    230.63905340    456.00000000   1560.00000000
PERCENT           152    18.13832736     10.23891032      1.05726841     35.97288164

------------------------ CLASS=2   NAME=PICEA MARIANA ------------------------

BIOM              152     2.15295132      0.70411313      0.83731329      3.83052444
DENSIT            152  1082.60526316    242.54118672    768.00000000   1740.00000000
PERCENT           152    24.77653172     31.27619493      1.96754290     98.94273468

--------------------- CLASS=2   NAME=POPULUS TREMULOIDES ---------------------

BIOM              152     0.01483037      0.05613047               0      0.44778544
DENSIT            152     6.31578947     23.02443880               0    156.00000000
PERCENT           152     0.06060000      0.23093284               0      1.66075843

---------------------- CLASS=3   NAME=BETULA PAPYRIFERA ----------------------

BIOM              121    14.19698717     10.39814990               0     27.59175110
DENSIT            121   174.24793388    127.65671943               0    444.00000000
PERCENT           121    42.49321918     28.36905346               0     71.19490303

------------------------ CLASS=3   NAME=PICEA GLAUCA ------------------------

BIOM              121     7.09215380      5.36365666      0.02085107     15.49766922
DENSIT            121   456.89256198    111.62973033    192.00000000    660.00000000
PERCENT           121    21.05612293     14.41904394      0.32330203     39.58251410
```

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                                              SAS

VARIABLE            N          MEAN          STANDARD          MINIMUM          MAXIMUM
                                             DEVIATION          VALUE            VALUE

------------------------- CLASS=3   NAME=PICEA MARIANA ------------------------

BIOM               121      3.20822356      1.89311674       0.73593497       6.42855930
DENSIT             121    684.99173554    180.55638528     384.00000000    1224.00000000
PERCENT            121     36.45066891     42.29209954       2.06524456      99.67671177

---------------------- CLASS=3   NAME=POPULUS TREMULOIDES ---------------------

BIOM               121               0               0                0                0
DENSIT             121               0               0                0                0
PERCENT            121               0               0                0                0

----------------------- CLASS=4   NAME=BETULA PAPYRIFERA ----------------------

BIOM               113     11.05210447      9.59329027                0      26.81298828
DENSIT             113     78.37168142     66.67969742                0     192.00000000
PERCENT            113     33.59289238     26.03135890                0      64.12923244

------------------------- CLASS=4   NAME=PICEA GLAUCA -------------------------

BIOM               113      8.04090919      6.36294467       0.01035703      15.81922913
DENSIT             113    268.24778761     73.97158371     144.00000000     408.00000000
PERCENT            113     25.64461516     19.47987007       0.11023146      56.93992037

------------------------- CLASS=4   NAME=PICEA MARIANA ------------------------

BIOM               113      4.07962655      3.20962097       0.51431769       9.38535500
DENSIT             113    433.27433628    171.45700460     192.00000000     852.00000000
PERCENT            113     40.76250609     44.47014858       1.46470778      99.88978003
```

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                                          SAS

VARIABLE          N         MEAN        STANDARD         MINIMUM         MAXIMUM
                                        DEVIATION         VALUE           VALUE

--------------------- CLASS=4   NAME=POPULUS TREMULOIDES --------------------

BIOM            113              0              0              0              0
DENSIT          113              0              0              0              0
PERCENT         113              0              0              0              0

---------------------- CLASS=5   NAME=BETULA PAPYRIFERA ---------------------

BIOM            100     4.70621331     4.56298895              0    15.08643436
DENSIT          100    24.60000000    23.90131225              0    84.00000000
PERCENT         100    22.29934714    19.70628999              0    53.93617339

----------------------- CLASS=5   NAME=PICEA GLAUCA ------------------------

BIOM            100     5.91729134     5.72007918     0.00425543    15.46292305
DENSIT          100   141.48000000    48.79031200    60.00000000   240.00000000
PERCENT         100    28.24428980    25.40431841     0.04626759    92.00177749

----------------------- CLASS=5   NAME=PICEA MARIANA -----------------------

BIOM            100     5.29612770     3.81237262     0.47518259     9.94857788
DENSIT          100   303.72000000   127.60957502   144.00000000   624.00000000
PERCENT         100    49.45638761    43.50403589     1.74358959    99.95375465

--------------------- CLASS=5   NAME=POPULUS TREMULOIDES --------------------

BIOM            100              0              0              0              0
DENSIT          100              0              0              0              0
PERCENT         100              0              0              0              0
```

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                                        SAS

VARIABLE               N          MEAN           STANDARD          MINIMUM           MAXIMUM
                                                 DEVIATION          VALUE             VALUE

----------------------- CLASS=6    NAME=BETULA PAPYRIFERA -----------------------

BIOM                  86     1.60449446        2.18745595                0        5.95176411
DENSIT                86     6.83720930        9.48293882                0       24.00000000
PERCENT               86    11.99124663       17.62770087                0       55.74130203

------------------------- CLASS=6    NAME=PICEA GLAUCA -------------------------

BIOM                  86     4.16815692        3.85831286       0.00199292       11.70565796
DENSIT                86    73.95348837       27.54073218      24.00000000      132.00000000
PERCENT               86    34.21648896       33.57030759       0.02229985       91.06227111

------------------------- CLASS=6    NAME=PICEA MARIANA -------------------------

BIOM                  86     5.64063734        3.58283932       0.74087864        9.50114727
DENSIT                86   212.93023256       73.70191006     108.00000000      396.00000000
PERCENT               86    53.79227756       39.36668319       6.45137353       99.97770796

---------------------- CLASS=6    NAME=POPULUS TREMULOIDES ----------------------

BIOM                  86              0                 0                0                 0
DENSIT                86              0                 0                0                 0
PERCENT               86              0                 0                0                 0

----------------------- CLASS=7    NAME=BETULA PAPYRIFERA -----------------------

BIOM                  60     1.26383053        1.80893339                0        4.23643875
DENSIT                60     4.00000000        5.70459226                0       12.00000000
PERCENT               60     7.31200096       10.48048540                0       24.55172466
```

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                                         SAS

VARIABLE          N         MEAN          STANDARD         MINIMUM          MAXIMUM
                                          DEVIATION         VALUE            VALUE

-------------------------- CLASS=7    NAME=PICEA GLAUCA ---------------------------

BIOM             60     3.39504538      2.48970876      0.00129891       6.01066303
DENSIT           60    49.80000000     22.18474052     24.00000000      84.00000000
PERCENT          60    34.98091990     30.29983357      0.01578935      80.95804671

-------------------------- CLASS=7    NAME=PICEA MARIANA --------------------------

BIOM             60     5.52415425      2.88005166      1.37624931       8.98193932
DENSIT           60   147.60000000     50.20203251     60.00000000     240.00000000
PERCENT          60    57.70710308     31.33611833     19.04199287      99.98422226

------------------------ CLASS=7    NAME=POPULUS TREMULOIDES ---------------------

BIOM             60              0               0               0                0
DENSIT           60              0               0               0                0
PERCENT          60              0               0               0                0

------------------------- CLASS=8    NAME=BETULA PAPYRIFERA ----------------------

BIOM             32     0.66670588      1.57411332               0       4.29791737
DENSIT           32     1.87500000      4.42682439               0      12.00000000
PERCENT          32     4.08138379      9.63864746               0      26.62346877

-------------------------- CLASS=8    NAME=PICEA GLAUCA ---------------------------

BIOM             32     2.98941702      2.05417053      0.00129891       5.93410969
DENSIT           32    40.87500000     19.00042444     24.00000000      72.00000000
PERCENT          32    37.34360611     21.53427103      0.02673284      61.51281467
```

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                                                   SAS

VARIABLE                N          MEAN          STANDARD          MINIMUM           MAXIMUM
                                                 DEVIATION         VALUE             VALUE

------------------------- CLASS=8   NAME=PICEA MARIANA -------------------------

BIOM                   32     4.02810127        1.46975282        1.53902626        6.48217869
DENSIT                 32    84.37500000       26.48158216       60.00000000      132.00000000
PERCENT                32    58.57502299       23.41229270       36.61773254       99.97328681

---------------------- CLASS=8   NAME=POPULUS TREMULOIDES ----------------------

BIOM                   32              0                 0                 0                 0
DENSIT                 32              0                 0                 0                 0
PERCENT                32              0                 0                 0                 0

----------------------- CLASS=9   NAME=BETULA PAPYRIFERA -----------------------

BIOM                   20              0                 0                 0                 0
DENSIT                 20              0                 0                 0                 0
PERCENT                20              0                 0                 0                 0

------------------------- CLASS=9   NAME=PICEA GLAUCA --------------------------

BIOM                   20     1.49247789        0.49347450        1.01149845        1.97345734
DENSIT                 20    18.00000000        6.15587011       12.00000000       24.00000000
PERCENT                20    32.91804396        5.20136221       24.65915120       40.04609717

------------------------- CLASS=9   NAME=PICEA MARIANA -------------------------

BIOM                   20     2.94670558        0.49849006        2.34989643        3.68209457
DENSIT                 20    46.80000000        9.45682711       36.00000000       60.00000000
PERCENT                20    67.08196219        5.20136122       59.95392218       75.34084880
```

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                                              SAS

VARIABLE           N           MEAN          STANDARD           MINIMUM           MAXIMUM
                                             DEVIATION           VALUE             VALUE

----------------------- CLASS=9    NAME=POPULUS TREMULOIDES ----------------------

BIOM              20              0              0                 0                 0
DENSIT            20              0              0                 0                 0
PERCENT           20              0              0                 0                 0

----------------------- CLASS=10   NAME=BETULA PAPYRIFERA ------------------------

BIOM              20     0.03706999     0.07144977                 0        0.25738084
DENSIT            20   111.60000000   213.85248236                 0      768.00000000
PERCENT           20     2.95369580     5.53322535                 0       19.29541136

-------------------------- CLASS=10    NAME=PICEA GLAUCA -------------------------

BIOM              20     0.23350583     0.40007539                 0        1.01149845
DENSIT            20   505.20000000   515.75612352                 0     1092.00000000
PERCENT           20     8.54329221    11.15161801                 0       29.90229758

------------------------- CLASS=10    NAME=PICEA MARIANA -------------------------

BIOM              20     1.51504124     0.57560133        0.88764024        2.39253139
DENSIT            20   544.20000000   530.72419242       24.00000000     1128.00000000
PERCENT           20    86.61580145    12.76373394       66.54490410      100.00000000

---------------------- CLASS=10   NAME=POPULUS TREMULOIDES ----------------------

BIOM              20     0.02345147     0.03844192                 0        0.12504244
DENSIT            20   130.80000000   211.49333696                 0      696.00000000
PERCENT           20     1.88722439     3.00544759                 0        9.37422249
```

APPENDIX A.5

SIMULATED STAND CHARACTERISTICS FOR PERMAFROST SITES WITH DEEP SPECIES' ACTIVE LAYER DEPTH REQUIREMENTS BY 20-YEAR AGE INCREMENTS. CLASS (age increment), BIOM (biomass t/ha), DENSIT (density stems/ha), PERCENT (relative biomass)

```
                                        SAS

VARIABLE          N          MEAN           STANDARD          MINIMUM            MAXIMUM
                                            DEVIATION           VALUE              VALUE

---------------------- CLASS=1    NAME=BETULA PAPYRIFERA ----------------------

BIOM            168      1.51024216        3.64162353               0        19.24522400
DENSIT          168    518.71428571      486.09726661               0      2136.00000000
PERCENT         167     28.32393338       20.17613095               0        68.79995616

------------------------ CLASS=1    NAME=PICEA GLAUCA ------------------------

BIOM            168      0.47697511        0.82929159      0.00000000         4.63230038
DENSIT          168   1613.14285714      341.08531052      0.00000000      2388.00000000
PERCENT         167     13.81846669        4.93960009      3.10712707        27.53500649

------------------------ CLASS=1    NAME=PICEA MARIANA -----------------------

BIOM            168      0.84663122        0.55121802      0.00000000         2.42026424
DENSIT          168   1792.21428571      338.68933963      0.00000000      2496.00000000
PERCENT         167     49.73163214       27.50929988      3.84532725        96.41296345

--------------------- CLASS=1    NAME=POPULUS TREMULOIDES --------------------

BIOM            168      0.30470806        0.70907944               0         3.29340172
DENSIT          168    438.21428571      569.17358036               0      2232.00000000
PERCENT         167      8.12599105       10.02320323               0        38.03119537

---------------------- CLASS=2    NAME=BETULA PAPYRIFERA ----------------------

BIOM            152      4.51808999        8.66640562               0        29.22715759
DENSIT          152    166.89473684      234.30740995               0       912.00000000
PERCENT         152     20.45662958       24.94221112               0        76.17282698
```

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                                              SAS

VARIABLE              N            MEAN          STANDARD          MINIMUM          MAXIMUM
                                                 DEVIATION          VALUE            VALUE

------------------------ CLASS=2   NAME=PICEA GLAUCA ------------------------

BIOM                152      2.13400343        2.79316690       0.02362661       9.09951115
DENSIT              152    945.39473684      252.06968862     396.00000000    1620.00000000
PERCENT             152     15.48676667       12.57759599       0.49541511      39.02465416

------------------------ CLASS=2   NAME=PICEA MARIANA ------------------------

BIOM                152      3.11355511        1.31054396       0.49724239       5.58642673
DENSIT              152   1282.02631579      283.72470444     504.00000000    1860.00000000
PERCENT             152     63.45378957       34.51394733       1.28706353      99.50461074

--------------------- CLASS=2   NAME=POPULUS TREMULOIDES ---------------------

BIOM                152      0.17259079        0.68200334                0       3.64432526
DENSIT              152     34.50000000      130.15797839                0     744.00000000
PERCENT             152      0.60283182        2.12741662                0      11.74625237

---------------------- CLASS=3   NAME=BETULA PAPYRIFERA ----------------------

BIOM                121      4.61496861       10.22464544                0      30.08100891
DENSIT              121     69.22314050      151.81905280                0     528.00000000
PERCENT             121     12.87397163       27.59614549                0      75.48830626

------------------------ CLASS=3   NAME=PICEA GLAUCA ------------------------

BIOM                121      1.94875338        3.39599417       0.01136762      10.22915173
DENSIT              121    469.88429752      162.57681211     192.00000000     900.00000000
PERCENT             121      8.82512182        9.80127878       0.15367519      38.43162205
```

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                                        SAS

VARIABLE          N          MEAN          STANDARD          MINIMUM          MAXIMUM
                                           DEVIATION           VALUE            VALUE

-------------------- CLASS=3   NAME=PICEA MARIANA --------------------

BIOM             121      5.65368543      2.64538308      0.24789160       9.30248833
DENSIT           121    822.04958678    244.29715005    264.00000000    1248.00000000
PERCENT          121     78.30092224     35.76001517      0.80645048      99.84633533

------------------ CLASS=3   NAME=POPULUS TREMULOIDES ------------------

BIOM             121               0               0               0                0
DENSIT           121               0               0               0                0
PERCENT          121               0               0               0                0

------------------- CLASS=4   NAME=BETULA PAPYRIFERA -------------------

BIOM             113      1.07956621      3.86118299               0      22.98707581
DENSIT           113     12.00000000     42.66815474               0     276.00000000
PERCENT          113      5.68869035     17.65235865               0      75.93349221

-------------------- CLASS=4   NAME=PICEA GLAUCA --------------------

BIOM             113      1.08329833      2.04409126      0.00640828       7.03768826
DENSIT           113    212.81415929     77.22168328    108.00000000     420.00000000
PERCENT          113     12.37845609     25.91051680      0.05615624      91.49732607

-------------------- CLASS=4   NAME=PICEA MARIANA --------------------

BIOM             113      7.98077534      3.75542761      0.23946160      12.66918564
DENSIT           113    574.30088496    187.74664183    156.00000000     852.00000000
PERCENT          113     81.93286870     35.74386782      0.81886341      99.94386876
```

```
                                          SAS

VARIABLE          N          MEAN         STANDARD         MINIMUM        MAXIMUM
                                          DEVIATION        VALUE          VALUE

-------------------- CLASS=4   NAME=POPULUS TREMULOIDES --------------------

BIOM             113              0              0              0              0
DENSIT           113              0              0              0              0
PERCENT          113              0              0              0              0

--------------------- CLASS=5   NAME=BETULA PAPYRIFERA ---------------------

BIOM             100              0              0              0              0
DENSIT           100              0              0              0              0
PERCENT          100              0              0              0              0

----------------------- CLASS=5   NAME=PICEA GLAUCA -----------------------

BIOM             100     0.56500742     1.08582779     0.00209790     3.92278862
DENSIT           100    97.32000000    34.36255891    36.00000000   192.00000000
PERCENT          100    15.30986171    30.31883785     0.01958033    89.22962385

----------------------- CLASS=5   NAME=PICEA MARIANA -----------------------

BIOM             100     8.96665374     4.29998994     0.47349709    13.59366226
DENSIT           100   383.40000000   146.50721360   132.00000000   624.00000000
PERCENT          100    84.69015285    30.31883678    10.77039106    99.98041794

-------------------- CLASS=5   NAME=POPULUS TREMULOIDES --------------------

BIOM             100              0              0              0              0
DENSIT           100              0              0              0              0
PERCENT          100              0              0              0              0
```

```
                                          SAS

VARIABLE            N         MEAN          STANDARD         MINIMUM          MAXIMUM
                                            DEVIATION        VALUE            VALUE

----------------------- CLASS=6   NAME=BETULA PAPYRIFERA -----------------------

BIOM               86            0              0               0                0
DENSIT             86            0              0               0                0
PERCENT            86            0              0               0                0

------------------------ CLASS=6   NAME=PICEA GLAUCA ------------------------

BIOM               86    0.35149243     0.61473548      0.00139304       1.75401306
DENSIT             86   48.00000000    16.56644376     24.00000000      84.00000000
PERCENT            86   11.27237981    20.67430975      0.01401310      60.19913460

------------------------ CLASS=6   NAME=PICEA MARIANA ------------------------

BIOM               86    8.07430181     3.83680148      1.15967083      13.63429165
DENSIT             86  242.65116279    85.45762864    108.00000000     408.00000000
PERCENT            86   88.72762334    20.67431882     39.80083267      99.98600329

--------------------- CLASS=6   NAME=POPULUS TREMULOIDES ---------------------

BIOM               86            0              0               0                0
DENSIT             86            0              0               0                0
PERCENT            86            0              0               0                0

----------------------- CLASS=7   NAME=BETULA PAPYRIFERA -----------------------

BIOM               60            0              0               0                0
DENSIT             60            0              0               0                0
PERCENT            60            0              0               0                0
```

```
                                          SAS

VARIABLE          N         MEAN          STANDARD          MINIMUM          MAXIMUM
                                          DEVIATION          VALUE            VALUE

------------------------ CLASS=7   NAME=PICEA GLAUCA ------------------------

BIOM             60      0.23014676      0.35487712      0.00129891      1.11771488
DENSIT           60     30.20000000      7.80873045     12.00000000     48.00000000
PERCENT          60      7.59043613     11.43180340      0.01578935     35.19869994

------------------------ CLASS=7   NAME=PICEA MARIANA ------------------------

BIOM             60      6.29588251      3.24860401      2.05773067     11.27821064
DENSIT           60    147.60000000     48.77176177     72.00000000    240.00000000
PERCENT          60     92.40957041     11.43180478     64.80136012     99.98422226

--------------------- CLASS=7   NAME=POPULUS TREMULOIDES ---------------------

BIOM             60               0               0               0               0
DENSIT           60               0               0               0               0
PERCENT          60               0               0               0               0

---------------------- CLASS=8   NAME=BETULA PAPYRIFERA ----------------------

BIOM             32               0               0               0               0
DENSIT           32               0               0               0               0
PERCENT          32               0               0               0               0

------------------------ CLASS=8   NAME=PICEA GLAUCA ------------------------

BIOM             32      0.04525342      0.10341909      0.00129891      0.28179228
DENSIT           32     23.25000000      6.04819355     12.00000000     36.00000000
PERCENT          32      1.99084179      4.68606152      0.02082137     14.66877545
```

```
                                          SAS
VARIABLE           N         MEAN        STANDARD         MINIMUM          MAXIMUM
                                         DEVIATION         VALUE            VALUE

--------------------- CLASS=8    NAME=PICEA MARIANA ---------------------

BIOM              32      5.00051007    1.60504396      1.63924217       7.26778603
DENSIT            32     90.37500000   19.03095950     48.00000000     120.00000000
PERCENT           32     98.00916805    4.68606447     85.33120593      99.97918800

------------------- CLASS=8    NAME=POPULUS TREMULOIDES -------------------

BIOM              32               0             0               0                0
DENSIT            32               0             0               0                0
PERCENT           32               0             0               0                0

-------------------- CLASS=9    NAME=BETULA PAPYRIFERA --------------------

BIOM              20               0             0               0                0
DENSIT            20               0             0               0                0
PERCENT           20               0             0               0                0

--------------------- CLASS=9    NAME=PICEA GLAUCA ----------------------

BIOM              20      0.00139776    0.00000000      0.00139776       0.00139776
DENSIT            20     24.00000000    0.00000000     24.00000000      24.00000000
PERCENT           20      0.03995609    0.00482833      0.03004395       0.04433218

--------------------- CLASS=9    NAME=PICEA MARIANA ---------------------

BIOM              20      3.54912410    0.45760198      3.15153122       4.65099239
DENSIT            20     54.00000000    7.28372374     48.00000000      72.00000000
PERCENT           20     99.96006189    0.00482616     99.95568777      99.96996956
```

```
                                    SAS

VARIABLE          N          MEAN          STANDARD         MINIMUM         MAXIMUM
                                           DEVIATION         VALUE           VALUE

---------------------- CLASS=9    NAME=POPULUS TREMULOIDES ---------------------

BIOM             20             0              0               0               0
DENSIT           20             0              0               0               0
PERCENT          20             0              0               0               0

---------------------- CLASS=10   NAME=BETULA PAPYRIFERA ----------------------

BIOM             20             0              0               0               0
DENSIT           20             0              0               0               0
PERCENT          20             0              0               0               0

------------------------- CLASS=10   NAME=PICEA GLAUCA -----------------------

BIOM             20    0.00083307     0.00024338      0.00073342      0.00139776
DENSIT           20   13.80000000     4.39617058     12.00000000     24.00000000
PERCENT          20    0.03280005     0.00710467      0.03009783      0.05760008

------------------------ CLASS=10   NAME=PICEA MARIANA -----------------------

BIOM             20    2.51403294     0.24369582      2.42526817      3.22654343
DENSIT           20   37.20000000     3.69352207     36.00000000     48.00000000
PERCENT          20   99.96720289     0.00710477     99.94238653     99.96990413

--------------------- CLASS=10   NAME=POPULUS TREMULOIDES --------------------

BIOM             20             0              0               0               0
DENSIT           20             0              0               0               0
PERCENT          20             0              0               0               0
```

APPENDIX A.6

REPORTED STAND CHARACTERISTICS FOR PERMAFROST SITES BY 20-YEAR AGE INCREMENTS.
CLASS(age increment), BIOM (biomass t/ha), DENSIT (density stems/ha),
PERCENT (relative biomass)

```
                                          SAS

VARIABLE          N         MEAN          STANDARD          MINIMUM           MAXIMUM
                                          DEVIATION         VALUE             VALUE

----------------------- CLASS=1   NAME=BETULA PAPYRIFERA ----------------------

BIOM            227     0.92318002      5.03120906            0       56.15296255
DENSIT          227    25.18444175    122.24467238            0     1320.09933748
PERCENT          80     8.72344059     22.01903819            0      100.00000000

------------------------ CLASS=1   NAME=LARIX LARICINA -------------------------

BIOM            227     0.01404781      0.21165154            0        3.18885205
DENSIT          227     0.13732168      2.06895972            0       31.17202124
PERCENT          80     0.03513663      0.31427161            0        2.81093073

------------------------- CLASS=1   NAME=PICEA GLAUCA -------------------------

BIOM            227    12.13751741     32.24998022            0      156.81309920
DENSIT          227   141.67388592    436.79995027            0     3869.88479837
PERCENT          80    52.42057240     46.60936223            0      100.00000000

------------------------- CLASS=1   NAME=PICEA MARIANA ------------------------

BIOM            227              0               0            0                 0
DENSIT          227              0               0            0                 0
PERCENT          80              0               0            0                 0

---------------------- CLASS=1   NAME=POPULUS BALSAMIFERA ---------------------

BIOM            227     1.99707025     12.97499818            0      131.64093033
DENSIT          227    33.09686900    186.90158231            0     1577.32534155
PERCENT          80     8.69501321     25.07174339            0       99.01384658
```

```
                                        SAS

VARIABLE            N          MEAN          STANDARD           MINIMUM           MAXIMUM
                                             DEVIATION            VALUE             VALUE

---------------------- CLASS=1    NAME=POPULUS TREMULOIDES ---------------------

BIOM              227    1.45632821      7.04079797                  0      70.84846318
DENSIT            227  147.20261205    595.76537404                  0    4637.65881733
PERCENT            80   30.12583716     44.00854906                  0     100.00000000

----------------------- CLASS=2    NAME=BETULA PAPYRIFERA ----------------------

BIOM               10   12.45589333     20.40005634                  0      54.62908359
DENSIT             10  740.46808870   1176.75619065                  0    3154.19793079
PERCENT             7   49.47762105     49.85362096                  0     100.00000000

------------------------ CLASS=2    NAME=LARIX LARICINA ------------------------

BIOM               10             0               0                  0                0
DENSIT             10             0               0                  0                0
PERCENT             7             0               0                  0                0

------------------------- CLASS=2    NAME=PICEA GLAUCA -------------------------

BIOM               10    0.06199278      0.11421268                  0       0.28167041
DENSIT             10   10.94085998     20.39469363                  0      49.16396675
PERCENT             7    0.18800314      0.30489030                  0       0.73287844

------------------------- CLASS=2    NAME=PICEA MARIANA ------------------------

BIOM               10             0               0                  0                0
DENSIT             10             0               0                  0                0
PERCENT             7             0               0                  0                0
```

```
                                          SAS
VARIABLE           N          MEAN         STANDARD          MINIMUM          MAXIMUM
                                           DEVIATION          VALUE            VALUE

-------------------- CLASS=2    NAME=POPULUS BALSAMIFERA --------------------

BIOM              10       3.62085686     11.45015476             0      36.20856859
DENSIT            10     191.73947031    606.33344353             0    1917.39470307
PERCENT            7      14.18101737     37.51944529             0      99.26712156

-------------------- CLASS=2    NAME=POPULUS TREMULOIDES --------------------

BIOM              10      22.18239683     38.76293390             0     100.51160356
DENSIT            10     887.85306012   1830.00481778             0    5610.96382331
PERCENT            7      36.15335844     47.63785608             0     100.00000000

--------------------- CLASS=3    NAME=BETULA PAPYRIFERA ---------------------

BIOM              20      18.44280156     29.49609732             0      93.08294604
DENSIT            20     375.21514370    578.07292785             0    1840.99752212
PERCENT           14      39.04921447     42.66032001             0      99.34775150

---------------------- CLASS=3    NAME=LARIX LARICINA -----------------------

BIOM              20                0               0             0                0
DENSIT            20                0               0             0                0
PERCENT           14                0               0             0                0

----------------------- CLASS=3    NAME=PICEA GLAUCA -----------------------

BIOM              20       1.78196151      4.62415490             0      20.29038532
DENSIT            20     127.21837456    263.76879645             0    1047.90523335
PERCENT           14      10.54889667     27.23011123             0     100.00000000
```

```
                                        SAS

VARIABLE          N        MEAN          STANDARD          MINIMUM         MAXIMUM
                                         DEVIATION         VALUE           VALUE

------------------------ CLASS=3   NAME=PICEA MARIANA ------------------------

BIOM             20              0               0               0               0
DENSIT           20              0               0               0               0
PERCENT          14              0               0               0               0

--------------------- CLASS=3   NAME=POPULUS BALSAMIFERA ---------------------

BIOM             20     6.14195415     19.15014959               0     72.91458860
DENSIT           20    57.91946756    177.71838783               0    674.65002530
PERCENT          14    14.47369442     36.09921970               0    100.00000000

--------------------- CLASS=3   NAME=POPULUS TREMULOIDES ---------------------

BIOM             20    15.64551164     26.38093449               0     85.05285063
DENSIT           20   410.83939907    728.23066653               0   2444.68517803
PERCENT          14    35.92819444     41.86116001               0    100.00000000

---------------------- CLASS=4   NAME=BETULA PAPYRIFERA ----------------------

BIOM              8     2.64569818      4.21536415               0     10.16025061
DENSIT            8    40.95284781     57.74760348               0    165.69534894
PERCENT           7    15.76211681     36.99171656               0     99.26327121

----------------------- CLASS=4   NAME=LARIX LARICINA ------------------------

BIOM              8              0               0               0               0
DENSIT            8              0               0               0               0
PERCENT           7              0               0               0               0
```

```
                                          SAS

VARIABLE             N         MEAN          STANDARD          MINIMUM          MAXIMUM
                                             DEVIATION          VALUE            VALUE

------------------------- CLASS=4   NAME=PICEA GLAUCA -------------------------

BIOM                 8     35.10790201    78.39749977                0     223.68148885
DENSIT               8    624.33721506  1360.29624935                0    3869.51711881
PERCENT              7     21.73200593    38.40799256                0      98.96280736

------------------------- CLASS=4   NAME=PICEA MARIANA -------------------------

BIOM                 8               0              0                0                0
DENSIT               8               0              0                0                0
PERCENT              7               0              0                0                0

---------------------- CLASS=4   NAME=POPULUS BALSAMIFERA ----------------------

BIOM                 8      0.14924322     0.38008461                0       1.08517635
DENSIT               8     13.05712066    25.85231878                0      69.35558260
PERCENT              7      0.23110148     0.41690166                0       1.04145339

---------------------- CLASS=4   NAME=POPULUS TREMULOIDES ----------------------

BIOM                 8     44.27920223    46.46091769                0     119.08440518
DENSIT               8    687.99943953   623.84443766                0    1391.90952588
PERCENT              7     62.27477578    45.43983820                0      99.42374306

----------------------- CLASS=5   NAME=BETULA PAPYRIFERA -----------------------

BIOM                 8               0              0                0                0
DENSIT               8               0              0                0                0
PERCENT              6               0              0                0                0
```

```
                                              SAS

VARIABLE              N           MEAN            STANDARD              MINIMUM            MAXIMUM
                                                  DEVIATION              VALUE              VALUE

---------------------- CLASS=5   NAME=LARIX LARICINA -----------------------

BIOM                  8              0                  0                   0                  0
DENSIT                8              0                  0                   0                  0
PERCENT               6              0                  0                   0                  0

----------------------- CLASS=5   NAME=PICEA GLAUCA -----------------------

BIOM                  8    21.57253252        49.27423823                   0       141.36804951
DENSIT                8   136.89991409       223.25780599                   0       648.28744741
PERCENT               6    36.45333973        49.47573055                   0       100.00000000

----------------------- CLASS=5   NAME=PICEA MARIANA -----------------------

BIOM                  8              0                  0                   0                  0
DENSIT                8              0                  0                   0                  0
PERCENT               6              0                  0                   0                  0

-------------------- CLASS=5   NAME=POPULUS BALSAMIFERA --------------------

BIOM                  8    30.34459153        59.99343341                   0       160.78497291
DENSIT                8   372.96617577       811.79071391                   0      2313.17497723
PERCENT               6    30.55033752        47.45169780                   0        99.30601493

-------------------- CLASS=5   NAME=POPULUS TREMULOIDES --------------------

BIOM                  8     4.17681038         6.77880869                   0        17.90520799
DENSIT                8   609.08113631      1089.33601460                   0      2419.32107027
PERCENT               6    32.99632275        50.22021506                   0        99.64876785
```

```
                                        SAS

VARIABLE          N         MEAN          STANDARD          MINIMUM          MAXIMUM
                                          DEVIATION         VALUE            VALUE

---------------------- CLASS=6   NAME=BETULA PAPYRIFERA ---------------------

BIOM              7     41.88397814     50.76204511              0     139.40775289
DENSIT            7    225.80291410    370.59027910              0    1041.90108643
PERCENT           7     39.82540090     46.30894736              0      99.19591153

----------------------- CLASS=6   NAME=LARIX LARICINA -----------------------

BIOM              7               0               0              0                0
DENSIT            7               0               0              0                0
PERCENT           7               0               0              0                0

------------------------ CLASS=6   NAME=PICEA GLAUCA ------------------------

BIOM              7     73.69749206     84.72924653     0.48489516     195.33686288
DENSIT            7    301.44003516    299.24505933     5.17199401     660.44264226
PERCENT           7     44.47634300     44.98994093     0.80408847      96.42031495

------------------------ CLASS=6   NAME=PICEA MARIANA -----------------------

BIOM              7               0               0              0                0
DENSIT            7               0               0              0                0
PERCENT           7               0               0              0                0

--------------------- CLASS=6   NAME=POPULUS BALSAMIFERA --------------------

BIOM              7      2.87444591      6.11263153              0      16.36900336
DENSIT            7     15.98480519     31.62007937              0      83.58267865
PERCENT           7      1.67782096      3.15639021              0       8.16506167
```

```
                                       SAS

VARIABLE          N          MEAN          STANDARD          MINIMUM          MAXIMUM
                                          DEVIATION           VALUE            VALUE

--------------------- CLASS=6    NAME=POPULUS TREMULOIDES ---------------------

BIOM              7    47.12129500    124.67122803               0     329.84906502
DENSIT            7   106.03916040    280.55324766               0     742.27412281
PERCENT           7    14.02043514     37.09458466               0      98.14304598

---------------------- CLASS=7    NAME=BETULA PAPYRIFERA ----------------------

BIOM              7    30.01717308     44.22545678               0      96.43973211
DENSIT            7   221.95949934    299.04313240               0     744.23181581
PERCENT           5    44.14879733     48.69497916               0      98.63310808

----------------------- CLASS=7    NAME=LARIX LARICINA -----------------------

BIOM              7              0               0               0                0
DENSIT            7              0               0               0                0
PERCENT           5              0               0               0                0

------------------------ CLASS=7    NAME=PICEA GLAUCA ------------------------

BIOM              7    44.06421630     58.91652797      0.00000000     133.49122836
DENSIT            7   306.45287636    404.18199555      0.00000000    1039.03898464
PERCENT           5    54.03857678     46.76562626      1.36689192      92.51230018

------------------------ CLASS=7    NAME=PICEA MARIANA -----------------------

BIOM              7              0               0               0                0
DENSIT            7              0               0               0                0
PERCENT           5              0               0               0                0
```

```
                                        SAS
VARIABLE          N        MEAN        STANDARD          MINIMUM          MAXIMUM
                                       DEVIATION          VALUE            VALUE

---------------------- CLASS=7   NAME=POPULUS BALSAMIFERA ----------------------

BIOM              7     1.74309083     4.61178485               0      12.20163581
DENSIT            7     7.81232319    20.66946433               0      54.68626235
PERCENT           5     1.67498057     3.74537041               0       8.37490284

---------------------- CLASS=7   NAME=POPULUS TREMULOIDES ----------------------

BIOM              7     0.12588097     0.33304974               0       0.88116678
DENSIT            7     0.60064881     1.58916739               0       4.20454170
PERCENT           5     0.13764532     0.30778429               0       0.68822659

----------------------- CLASS=8   NAME=BETULA PAPYRIFERA -----------------------

BIOM              3     3.63640035     3.94948882      0.19790833       7.95007141
DENSIT            3    37.23401478    23.23007910     16.46635828      62.32039069
PERCENT           3     2.74079673     3.38488023      0.15022844       6.57066784

------------------------ CLASS=8   NAME=LARIX LARICINA -------------------------

BIOM              3              0              0               0                0
DENSIT            3              0              0               0                0
PERCENT           3              0              0               0                0

------------------------- CLASS=8   NAME=PICEA GLAUCA --------------------------

BIOM              3   135.37002018    30.37751252    109.77497190     168.93924127
DENSIT            3   567.63412352    71.81098455    484.71414978     609.25525649
PERCENT           3    93.09915225     3.17306937     90.72810046      96.70375943
```

```
                                        SAS

VARIABLE          N          MEAN          STANDARD         MINIMUM          MAXIMUM
                                          DEVIATION          VALUE            VALUE

------------------------ CLASS=8   NAME=PICEA MARIANA ------------------------

BIOM              3              0                0               0                0
DENSIT            3              0                0               0                0
PERCENT           3              0                0               0                0

--------------------- CLASS=8   NAME=POPULUS BALSAMIFERA ---------------------

BIOM              3              0                0               0                0
DENSIT            3              0                0               0                0
PERCENT           3              0                0               0                0

--------------------- CLASS=8   NAME=POPULUS TREMULOIDES ---------------------

BIOM              3     6.53687252       4.92204698      3.26831083      12.19780519
DENSIT            3    16.02722432       8.89533839      6.92448785      24.69953743
PERCENT           3     4.16005102       2.15307413      2.70123169       6.63290924

---------------------- CLASS=9   NAME=BETULA PAPYRIFERA ----------------------

BIOM              4    29.51356835      55.91943928               0     113.33356665
DENSIT            4   169.09698382     273.51999047               0     576.46107663
PERCENT           4    25.56703079      49.63165417               0     100.00000000

----------------------- CLASS=9   NAME=LARIX LARICINA ------------------------

BIOM              4              0                0               0                0
DENSIT            4              0                0               0                0
PERCENT           4              0                0               0                0
```

```
                                        SAS

VARIABLE            N          MEAN        STANDARD            MINIMUM          MAXIMUM
                                           DEVIATION            VALUE            VALUE

------------------------ CLASS=9    NAME=PICEA GLAUCA ------------------------

BIOM                4    127.39982536    89.52302069               0     207.68600247
DENSIT              4    617.35573973   421.16392480               0     896.76557209
PERCENT             4     73.78712558    49.20301557               0      99.87175883

------------------------ CLASS=9    NAME=PICEA MARIANA -----------------------

BIOM                4               0              0               0                0
DENSIT              4               0              0               0                0
PERCENT             4               0              0               0                0

-------------------- CLASS=9    NAME=POPULUS BALSAMIFERA ---------------------

BIOM                4      1.07590439     2.15180879               0       4.30361757
DENSIT              4     18.68261609    37.36523217               0      74.73046434
PERCENT             4      0.64584363     1.29168726               0       2.58337451

-------------------- CLASS=9    NAME=POPULUS TREMULOIDES ---------------------

BIOM                4               0              0               0                0
DENSIT              4               0              0               0                0
PERCENT             4               0              0               0                0

-------------------- CLASS=10    NAME=BETULA PAPYRIFERA ----------------------

BIOM                4      0.02219093     0.04438186               0       0.08876372
DENSIT              4      9.17750020    18.35500039               0      36.71000078
PERCENT             4      0.01713843     0.03427685               0       0.06855370
```

```
                                         SAS

VARIABLE       N        MEAN          STANDARD       MINIMUM        MAXIMUM
                                      DEVIATION      VALUE          VALUE

------------------- CLASS=10    NAME=LARIX LARICINA -------------------

BIOM           4               0              0              0              0
DENSIT         4               0              0              0              0
PERCENT        4               0              0              0              0

------------------- CLASS=10    NAME=PICEA GLAUCA --------------------

BIOM           4    123.24792560    36.22483308    70.52508373   150.68891773
DENSIT         4    597.64139516   274.86657161   282.20237176   838.11257049
PERCENT        4     91.97486604    16.00459807    67.96801788   100.00000000
------------------- CLASS=10    NAME=PICEA MARIANA -------------------

BIOM           4               0              0              0              0
DENSIT         4               0              0              0              0
PERCENT        4               0              0              0              0

----------------- CLASS=10    NAME=POPULUS BALSAMIFERA -----------------

BIOM           4               0              0              0              0
DENSIT         4               0              0              0              0
PERCENT        4               0              0              0              0

----------------- CLASS=10    NAME=POPULUS TREMULOIDES -----------------

BIOM           4     16.77591542    33.55183084              0    67.10366169
DENSIT         4     89.79777541   179.59555082              0   359.19110164
PERCENT        4      8.00799553    16.01599106              0    32.03198212
```

APPENDIX B.1

SIMULATED SOIL CHARACTERISTICS FOR PERMAFROST SITES WITH LOWEST BLACK SPRUCE COMPOSITION BY 20-YEAR AGE INCREMENTS. CLASS (age increment), ACTDPT (active layer depth in cm), ORGANIC (organic layer depth in cm)

```
                                        SAS

VARIABLE           N          MEAN         STANDARD        MINIMUM         MAXIMUM
                                           DEVIATION        VALUE           VALUE

-------------------------------- CLASS=1 ----------------------------------

ACTDPT           168    132.30849284    50.21756078               0    258.11987305
ORGNIC           168     19.44554665     4.40541227               0     31.60858154

-------------------------------- CLASS=2 ----------------------------------

ACTDPT           152    137.10510495    46.29473354     51.80027771    260.99536133
ORGNIC           152     20.96113014     4.58159364     18.66220093     33.60058594

-------------------------------- CLASS=3 ----------------------------------

ACTDPT           121    125.49207161    41.68955606     53.67854309    187.54064941
ORGNIC           121     22.71033017     5.34738883     19.80218506     35.59257507

-------------------------------- CLASS=4 ----------------------------------

ACTDPT           113    101.85826192    29.37095244     55.45295715    159.89871216
ORGNIC           113     24.15049825     5.82942947     20.94216919     37.58448792

-------------------------------- CLASS=5 ----------------------------------

ACTDPT           100     91.22772659    28.09213786     57.59066772    160.62370300
ORGNIC           100     25.83348541     6.44258230     22.08215332     39.57637024

-------------------------------- CLASS=6 ----------------------------------

ACTDPT            86     86.77842659    18.89355079     57.97505188    125.18052673
ORGNIC            86     27.63033596     7.20398695     23.22213745     41.56825256
```

```
                                         SAS
VARIABLE            N           MEAN        STANDARD          MINIMUM         MAXIMUM
                                            DEVIATION           VALUE           VALUE

------------------------------------ CLASS=7 ------------------------------------

ACTDPT             60    72.56695709      7.06281993     61.23074341     88.02584839
ORGNIC             60    30.80707550      8.43018652     24.36212158     43.56013489

------------------------------------ CLASS=8 ------------------------------------

ACTDPT             32    70.48964405      3.93819997     64.10049438     82.17227173
ORGNIC             32    29.89569235      7.56724083     25.50210571     44.25729370

------------------------------------ CLASS=9 ------------------------------------

ACTDPT             20    68.35847549      4.28341505     58.54864502     75.31884766
ORGNIC             20    27.40724106      0.54467575     26.64208984     28.32148743

------------------------------------ CLASS=10 -----------------------------------

ACTDPT             20    71.09384079      3.62687054     64.79695129     76.55378723
ORGNIC             20    29.36728897      0.58924047     28.42109680     30.31349182
```

APPENDIX B.2

SIMULATED SOIL CHARACTERISTICS FOR PERMAFROST SITES WITH HIGHEST BLACK SPRUCE COMPOSITION BY 20-YEAR AGE INCREMENTS. CLASS (age increment), ACTDPT (active layer depth in cm), ORGANIC (organic layer depth in cm)

```
                                         SAS

VARIABLE           N          MEAN          STANDARD         MINIMUM          MAXIMUM
                                            DEVIATION         VALUE            VALUE

------------------------------------ CLASS=1 -------------------------------------

ACTDPT            168     139.31811923     65.70882225               0     288.37402344
ORGNIC            168      14.78994057      6.53396042               0      31.65118408

------------------------------------ CLASS=2 -------------------------------------

ACTDPT            152     127.73241846     63.60526639     51.83389282     258.35327148
ORGNIC            152      16.80183510      6.83486489     11.10246754      33.64318848

------------------------------------ CLASS=3 -------------------------------------

ACTDPT            121      89.87896186     35.77635082     53.71725464     222.99243164
ORGNIC            121      19.74246165      7.37301518     12.24245167      35.63517761

------------------------------------ CLASS=4 -------------------------------------

ACTDPT            113      75.80274572     12.33411677     55.48690796     120.94815063
ORGNIC            113      21.83383448      7.70906309     13.38243580      37.62709045

------------------------------------ CLASS=5 -------------------------------------

ACTDPT            100      72.60386841      9.36961338     57.62568665      98.54653931
ORGNIC            100      24.18433308      8.23290237     14.52241993      39.61897278

------------------------------------ CLASS=6 -------------------------------------

ACTDPT             86      71.96769590      7.86879902     58.01109314      87.91256714
ORGNIC             86      25.86592393      9.02302047     15.66240406      41.61085510
```

```
                                        SAS

VARIABLE          N          MEAN       STANDARD        MINIMUM        MAXIMUM
                                        DEVIATION         VALUE          VALUE

---------------------------------- CLASS=7 ------------------------------------

ACTDPT           60    71.29153366    11.71336601    60.24641418   114.10978699
ORGNIC           60    27.75173594    10.78121543    17.27099609    43.60273743

---------------------------------- CLASS=8 ------------------------------------

ACTDPT           32    70.93427992     5.05516986    63.95130920    81.91839600
ORGNIC           32    27.89960003     8.84711196    19.26298523    44.29989624

---------------------------------- CLASS=9 ------------------------------------

ACTDPT           20    74.08912964     4.85534870    66.43037415    83.73875427
ORGNIC           20    26.36541443     0.58923932    25.41921997    27.31161499

---------------------------------- CLASS=10 -----------------------------------

ACTDPT           20    72.86621628     5.78871887    64.70318604    84.34078979
ORGNIC           20    28.35741043     0.58924034    27.41120911    29.30360413
```

VITA

Daryl Moorhead was born December 1, 1954, in Columbus, Ohio. He received a Bachelor of Science degree from The Ohio State University in June 1978 and a Master of Science degree from Texas A&M University in December 1981. He is married and has two children.