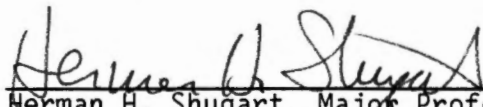
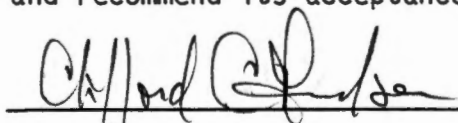


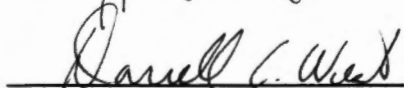
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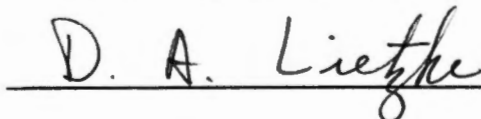
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Herman H. Shugart, Major Professor

We have read this dissertation  
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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

AG-VET-MED.

Thesis  
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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.

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## 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 (Vioreck 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 Vioreck 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<br>United States | Botkin et al.<br>1972     |
| FORET    | Hardwood                   | Tennessee<br>United States     | Shugart and West<br>1977  |
| FORICO   | Montane Rain<br>Forest     | Puerto Rico                    | Doyle et al. 1980         |
| BRIND    | Montane<br>Eucalyptus      | Australia                      | Shugart and Noble<br>1981 |
| KIAMBRAM | Subtropical<br>Rain Forest | Australia                      | Shugart et al.<br>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. Monthly 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.

## ANNUAL TEMPERATURE CURVES

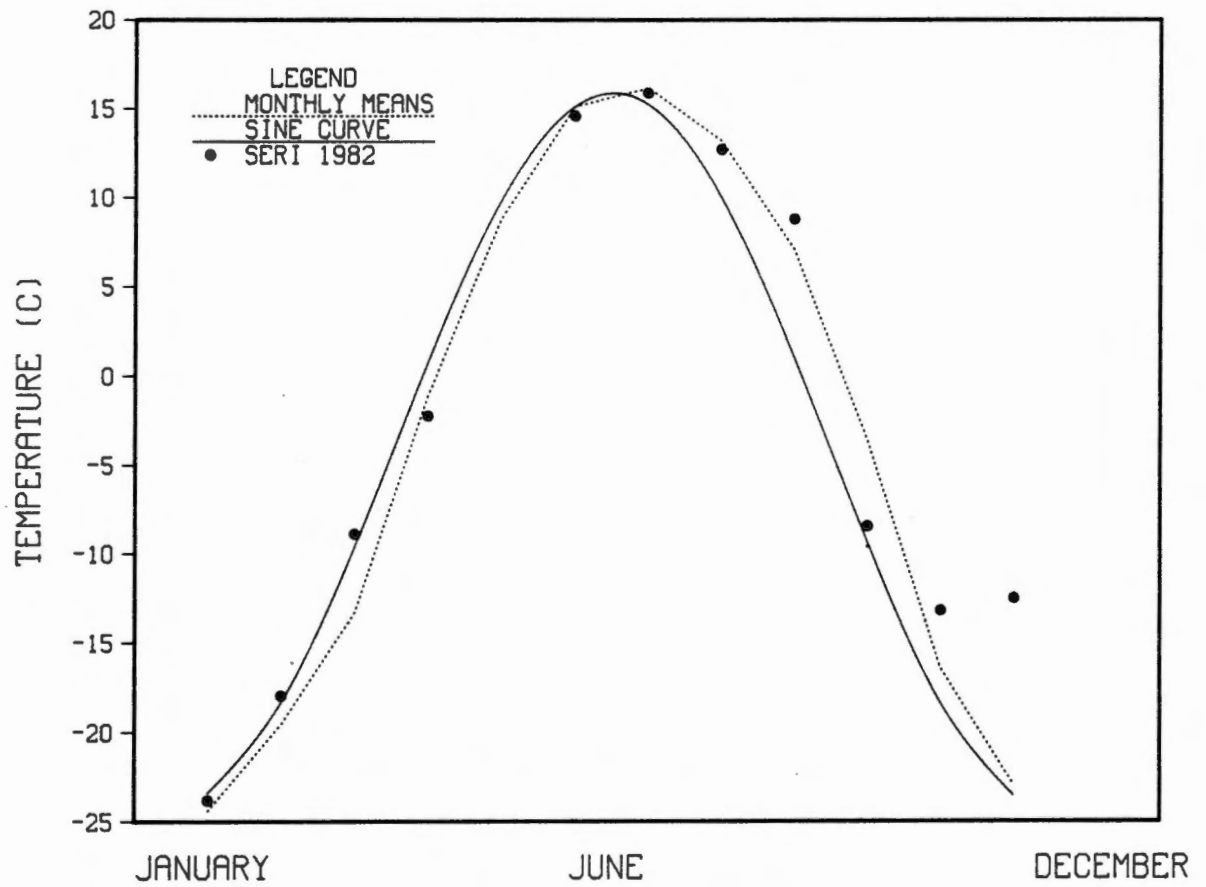


Figure 2.1. Annual ambient air temperature curves for Fairbanks, Alaska. Monthly mean values from NOAA (1977).

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

| Month    | Sine   |         | Mean   |         | Day    |         |
|----------|--------|---------|--------|---------|--------|---------|
|          | 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 meteorological 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  $(\text{cal})(\text{cm}^{-2})(\text{day}^{-1})$  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.,  $(\text{kJ})(\text{m}^{-2})(\text{day}^{-1})$  or  $(\text{cal})(\text{cm}^{-2})(\text{day}^{-1})$  (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 Geophysical 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  $(\text{kJ})(\text{m}^{-2})(\text{day}^{-1})$ , Ratio = Barkstrom/Klein.

| Month | 43 degrees latitude |          |       | 65 degrees latitude |          |       |
|-------|---------------------|----------|-------|---------------------|----------|-------|
|       | 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  |

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

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

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

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.

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

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.

| Month | Barkstrom |         | Klein   |         |
|-------|-----------|---------|---------|---------|
|       | 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.

| Month | Barkstrom |         | Klein   |         |
|-------|-----------|---------|---------|---------|
|       | 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  $(\text{cal})(\text{cm}^{-2})(\text{day}^{-1})$ .

| 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  $(\text{cal})(\text{cm}^{-2})(\text{day}^{-1})$ , Ratio = diffuse/direct, SERI data from 1982.

| Month | SERI   |         |       | Page   |         |       |
|-------|--------|---------|-------|--------|---------|-------|
|       | 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  |

## AVERAGE DAILY SUNLIGHT

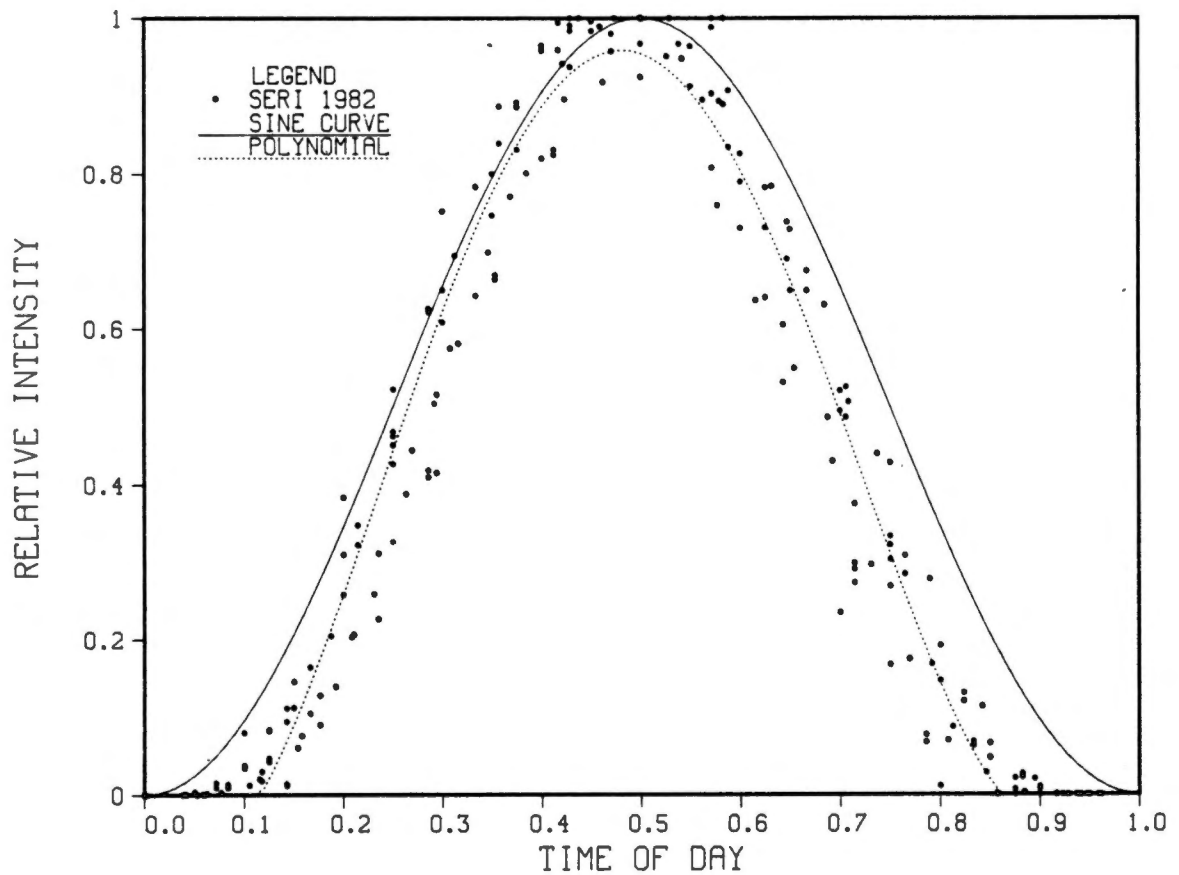


Figure 3.1. Diurnal relative sunlight (scaled 0.0 to 1.0) intensity curves incident to a horizontal surface at 65 degrees north latitude. September global values.

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  $(\text{cal})(\text{cm}^{-2})(\text{day}^{-1})$ , 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  $(\text{cal})(\text{cm}^{-2})(\text{day}^{-1})$ , 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      |

## JUNE DAILY SUNLIGHT

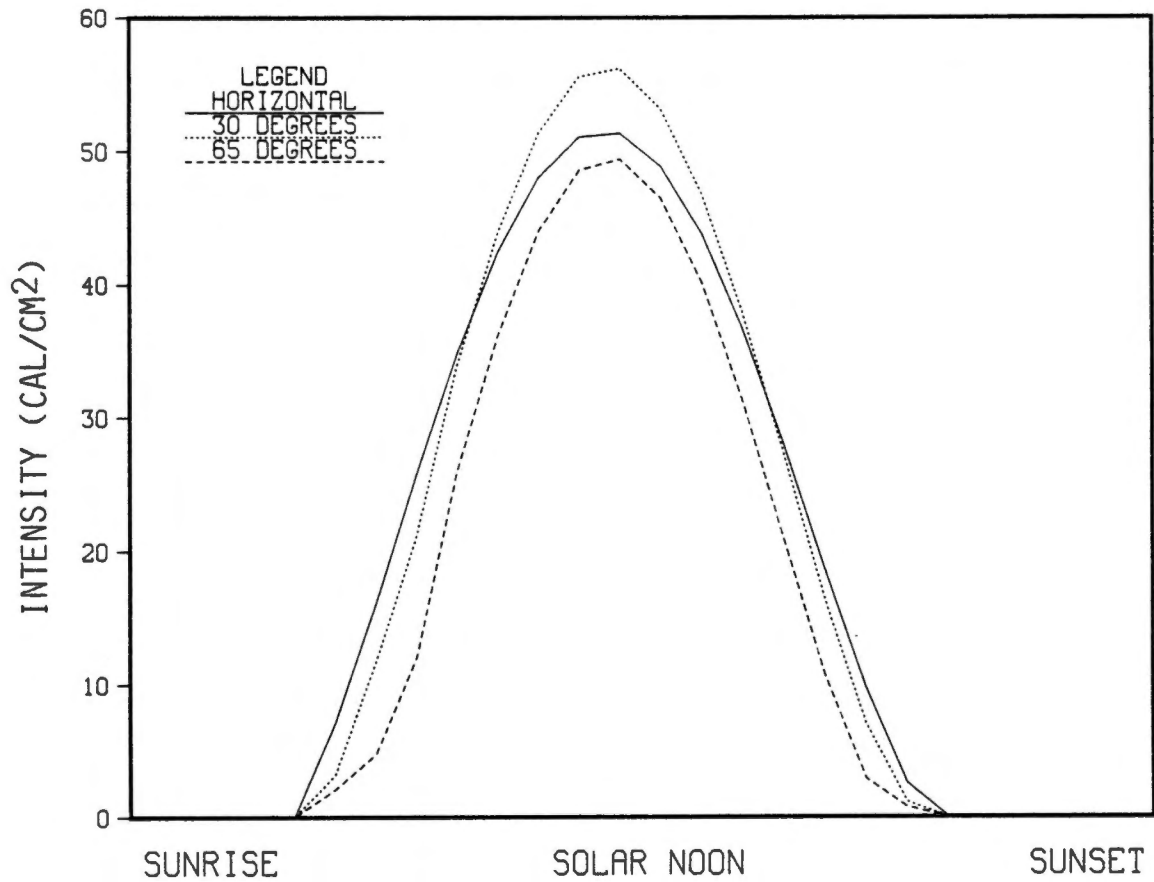


Figure 3.2. Simulated diurnal sunlight pattern incident to three south-facing slopes of varying inclination.

## JUNE DAILY SUNLIGHT

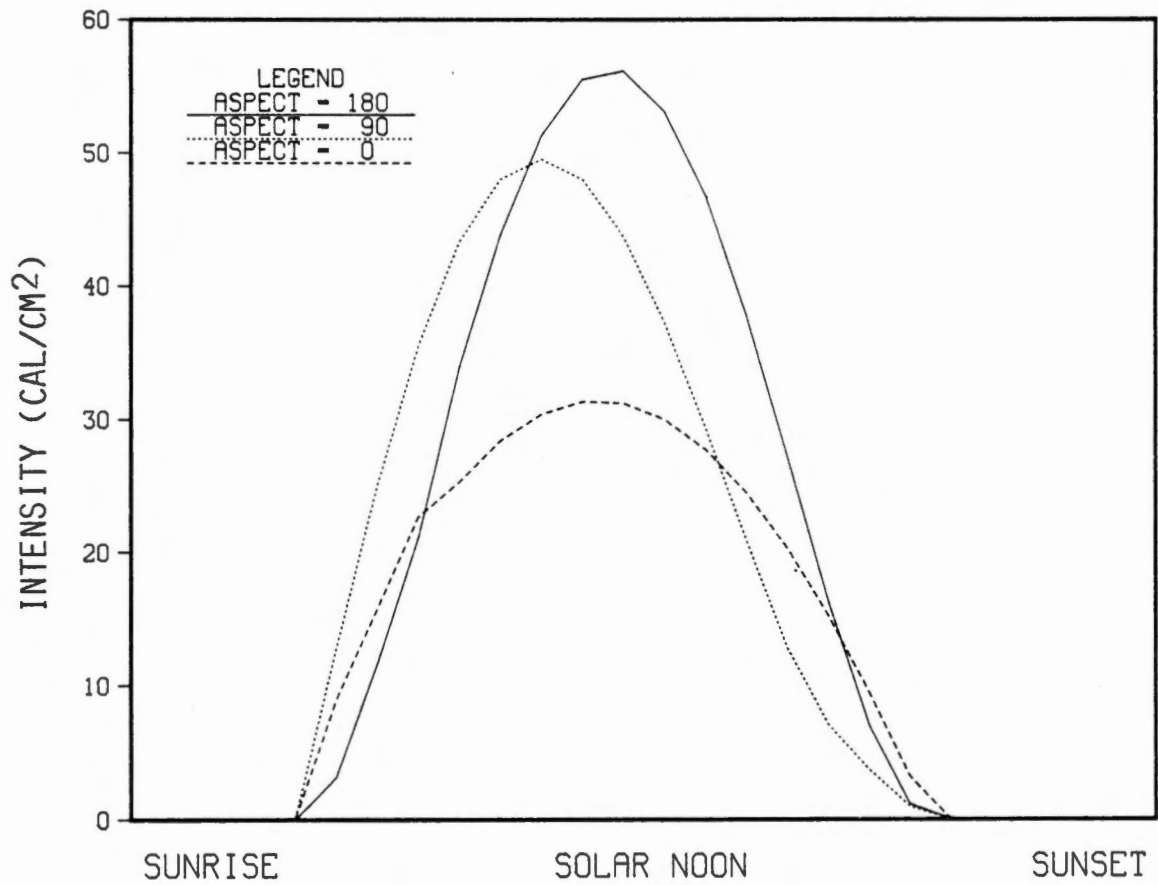


Figure 3.3. Simulated diurnal sunlight pattern incident to three inclined surfaces (30 degree slope) of varying aspect.

## 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.

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

$$TE = \sum^{12} (TMON)$$

$$A = 4.000001 ( 0.675(TE^3) - 77.1(TE^2) + 17920.0(TE) + 492390.0)$$

$$U = 1.6(10(TMEAN/TE))A)C$$

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.

$$\text{EVAP} = \text{AVAIL}(\exp(-\text{FIELD}/\text{AVAIL}))$$

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.

$$\text{VALUE} = \text{DRAIN}(\text{SAT}-\text{FC}) + \text{FC}$$

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 (cal)(cm<sup>-2</sup>)(hr<sup>-1</sup>)(°C<sup>-1</sup>)

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 ( $\text{g/cm}^3$ ), 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).

| Year | Evaporation |       |       |       |      | Precipitation |
|------|-------------|-------|-------|-------|------|---------------|
|      | May         | Jun   | Jul   | Aug   | Sep  |               |
| 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 | <u>Experimental Station</u> |                  | Air Port<br>Estimated |
|------|-------|-----------------------------|------------------|-----------------------|
|      |       | <u>Observed</u>             | <u>Estimated</u> |                       |
| 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

## WHITE SPRUCE SOIL MOISTURE REGIME

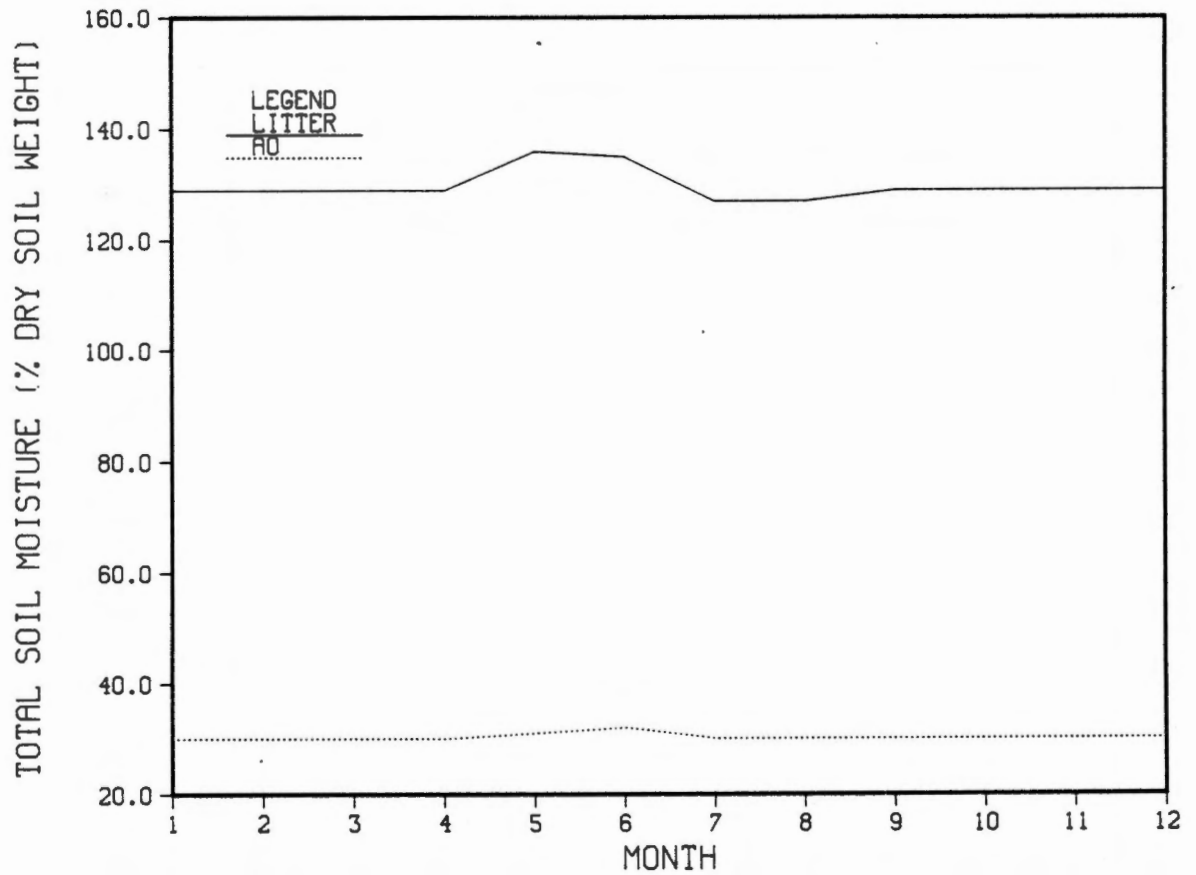


Figure 4.1. Moisture content of litter and surface soil layer in a white spruce forest through time.

## BLACK SPRUCE SOIL MOISTURE REGIME

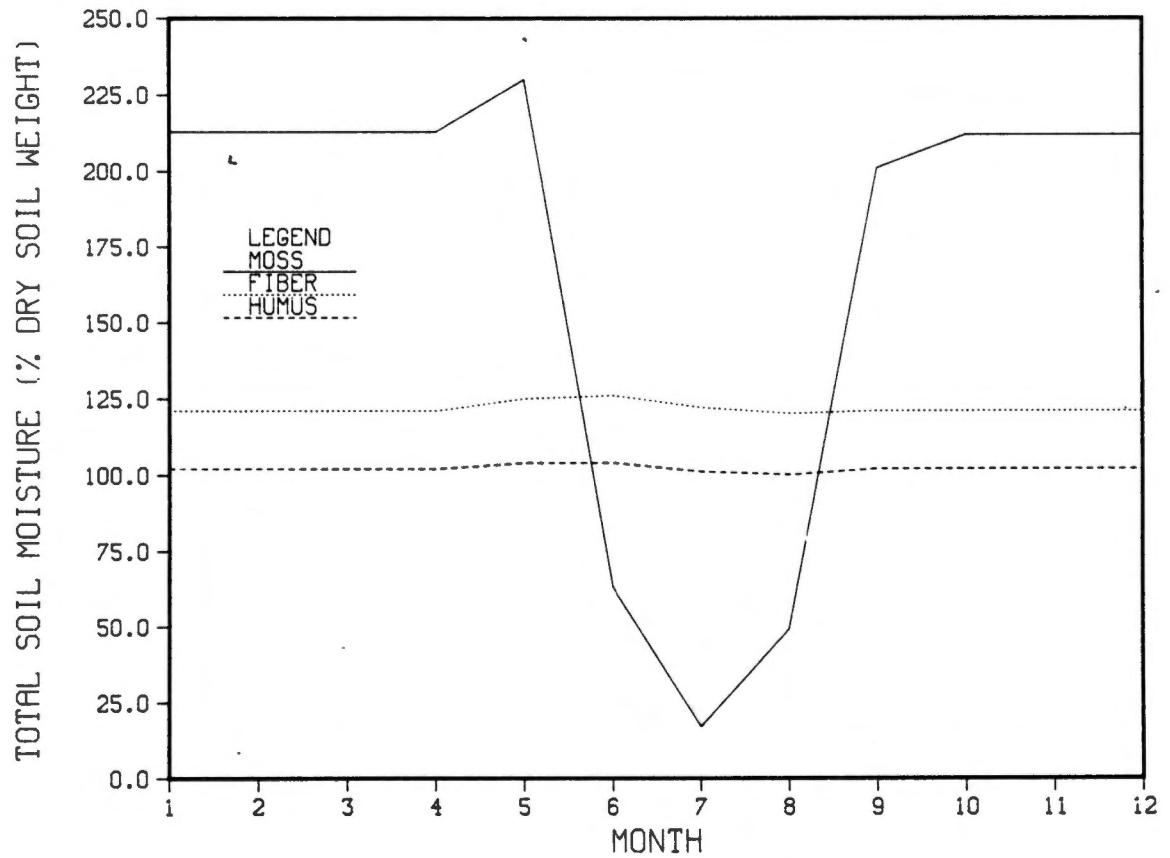


Figure 4.2. Moisture content of organic forest floor layers in a black spruce forest through time.

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 et 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.

$$\text{DEGD} = (Q/24)(R_1 + R_2 + R_3/2)$$

$$Q = 80.0w$$

$$R = h/k$$

DEGD : Number of degree days required

Q : Heat of fusion of water (Cal)(m<sup>-3</sup>)

w : Water content (kg)(m<sup>-3</sup>)

R : Thermal resistance (m<sup>2</sup>)(hr)(°C)(Cal<sup>-1</sup>) of all layers

h : Soil layer depth (m)

k : Thermal conductivity (Cal)(m<sup>-1</sup>)(hr<sup>-1</sup>)(°C<sup>-1</sup>)

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  $0.5 \text{ g/cm}^3$  were calculated as follows.

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

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

$w$  : Water content (percent dry soil weight)

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

Conductivities of frozen soils ( $\text{RHO} > 0.5 \text{ g/cm}^3$ ) were estimated as follows.

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

$\alpha = 0.22 \text{RHO}$

$\beta = .008 \text{RHO}$

Conductivities were transformed to units of  $(\text{Cal})(\text{m}^{-1})(\text{hr}^{-1})(^{\circ}\text{C}^{-1})$  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<sup>3</sup>, 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.

$$Q = kat(T_u - T_l)/h$$

Q : Heat transferred

k : Thermal conductivity

a : Surface area

t : Time span

T<sub>u</sub> : Upper layer temperature

T<sub>l</sub> : 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  $0.15 \text{ (Cal)(m}^{-1}\text{)(hr}^{-1}\text{)(}^{\circ}\text{C}^{-1}\text{)}$  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 |

## WHITE SPRUCE SOIL FREEZE-THAW CYCLE

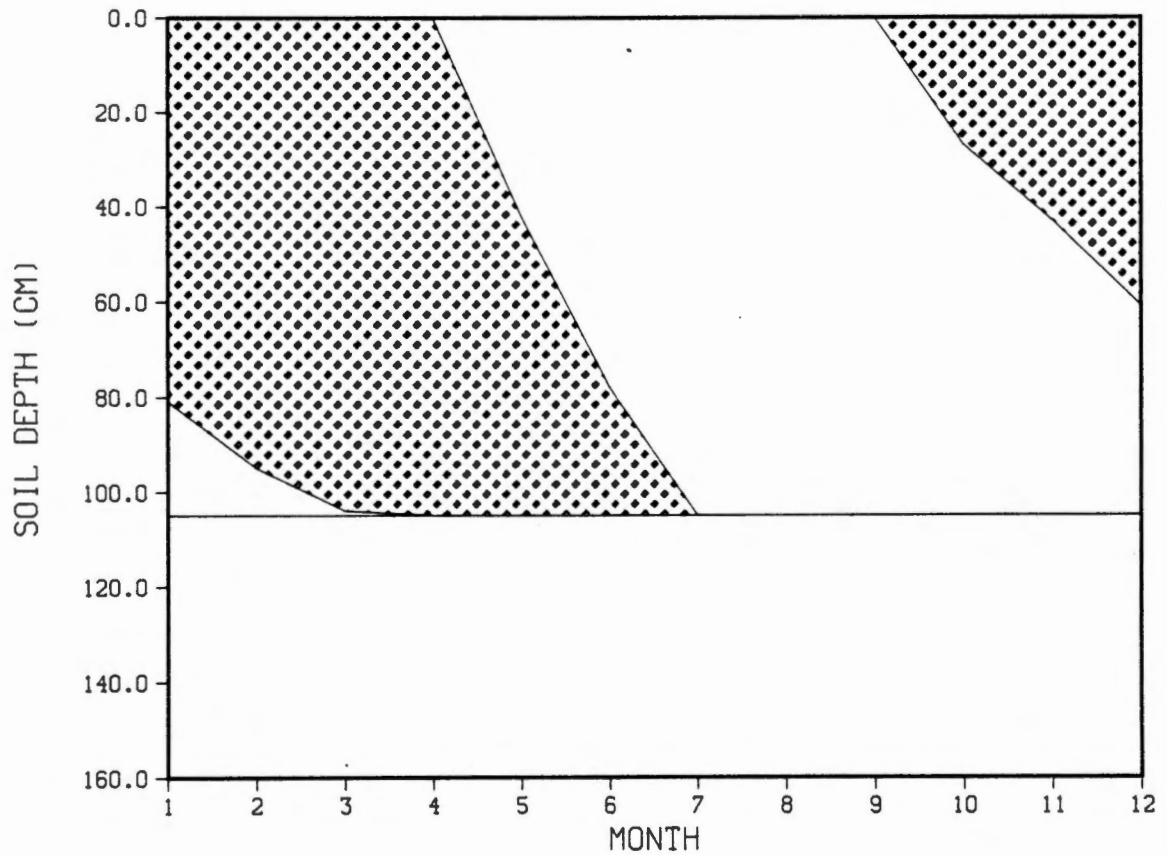


Figure 5.1. White spruce forest soil annual freeze-thaw cycle. Deep mineral soil moisture content at 33% field capacity, with full sunlight input. Stippled area represents frozen soil.

Sunlight energy flow through the soil litter layer was limited to about 3% of the total available sunlight ( $9602 \text{ (cal)(cm}^{-2}\text{)(month}^{-1}\text{)}$ ). 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 ( $6527 \text{ (cal)(cm}^{-2}\text{)(month}^{-1}\text{)}$ ) 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 |

## BLACK SPRUCE SOIL FREEZE-THAW CYCLE

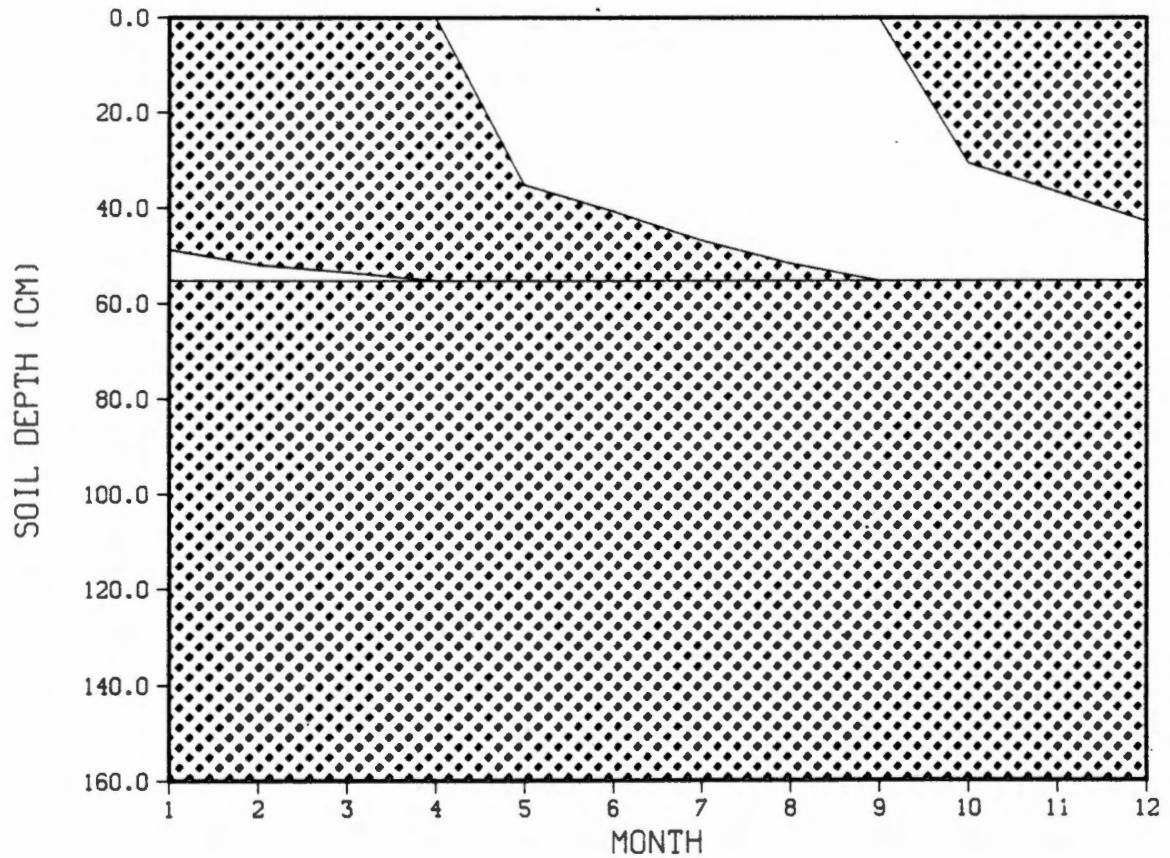


Figure 5.2. Black spruce forest soil annual freeze-thaw cycle. Deep mineral soil moisture content at saturation, with full sunlight input. Stippled area represents frozen soil.

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<br>(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 |

## BARE SOIL FREEZE-THAW CYCLE

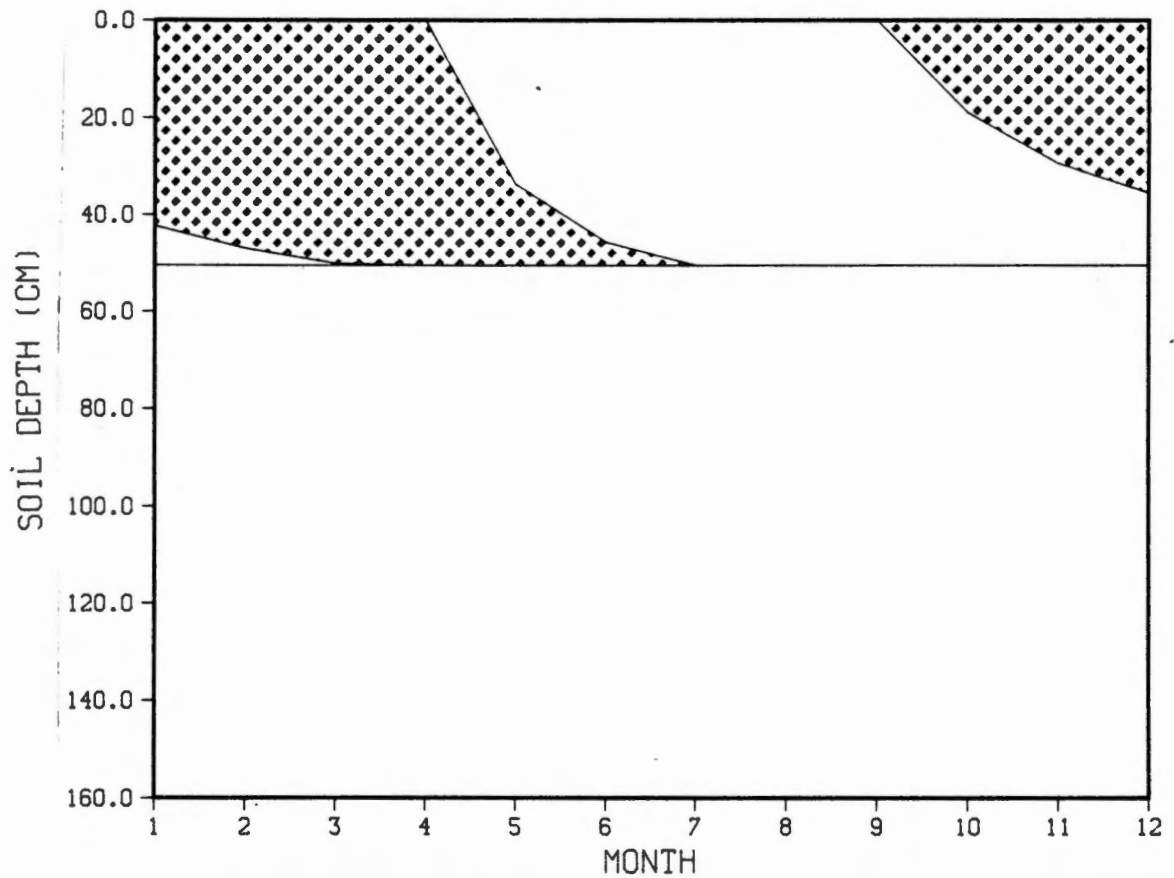


Figure 5.3. Bare mineral soil annual freeze-thaw cycle. Deep mineral soil moisture content at saturation, with full sunlight input. Stippled area represents frozen soil.

(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.

$$d(D^2H)/dt = RLA(1-(DH/D_{max}H_{max}))$$

- R : Growth rate parameter  
 LA : Leaf area (cm<sup>2</sup>)  
 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).

$$H = 137 + b_2D - b_3D^2$$

The values of  $b_2$  and  $b_3$  were determined by setting  $H = H_{\max}$  (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.

$$b_2 = 2(H_{\max} - 137)/D_{\max}$$

$$b_3 = (H_{\max} - 137)/D_{\max}^2$$

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 ( $R_s$ ) and intolerant ( $R_i$ ) trees.

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

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

$AL$  : 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.

$$T = 4(DEGD - DEGD_{min})(DEGD_{max} - DEGD)/(DEGD_{max} - DEGD_{min})^2$$

$T$  : Value from 0.0 to 1.0

$DEGD$  : Available growing degree days

$DEGD_{min}$  : Minimum value in species range

$DEGD_{max}$  : Maximum value in species range

Available growing degree days ( $DEGD$ ) was used as an index to this thermal relationship ( $5^\circ\text{C}$  base).

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

$$S = 1 - \text{BAR} / \text{SOILQ}$$

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.

$$\text{GM} = \text{ACTDPT}^2 / (\text{ACTDPT}^2 + \text{ACTmin}^2)$$

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.

$$\ln(\text{BIO}) = \alpha + \beta(\ln(\text{dbh}))$$

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 (SPRTND) 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 suppressed 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 suppressed state. Black and white spruce, however, are extremely tolerant and may survive up to 150 years of suppression. 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 AO 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 (ACT<sub>min</sub>) 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 two types with the former attaining a maximum of about 45 t/ha (Fig. 6.2),

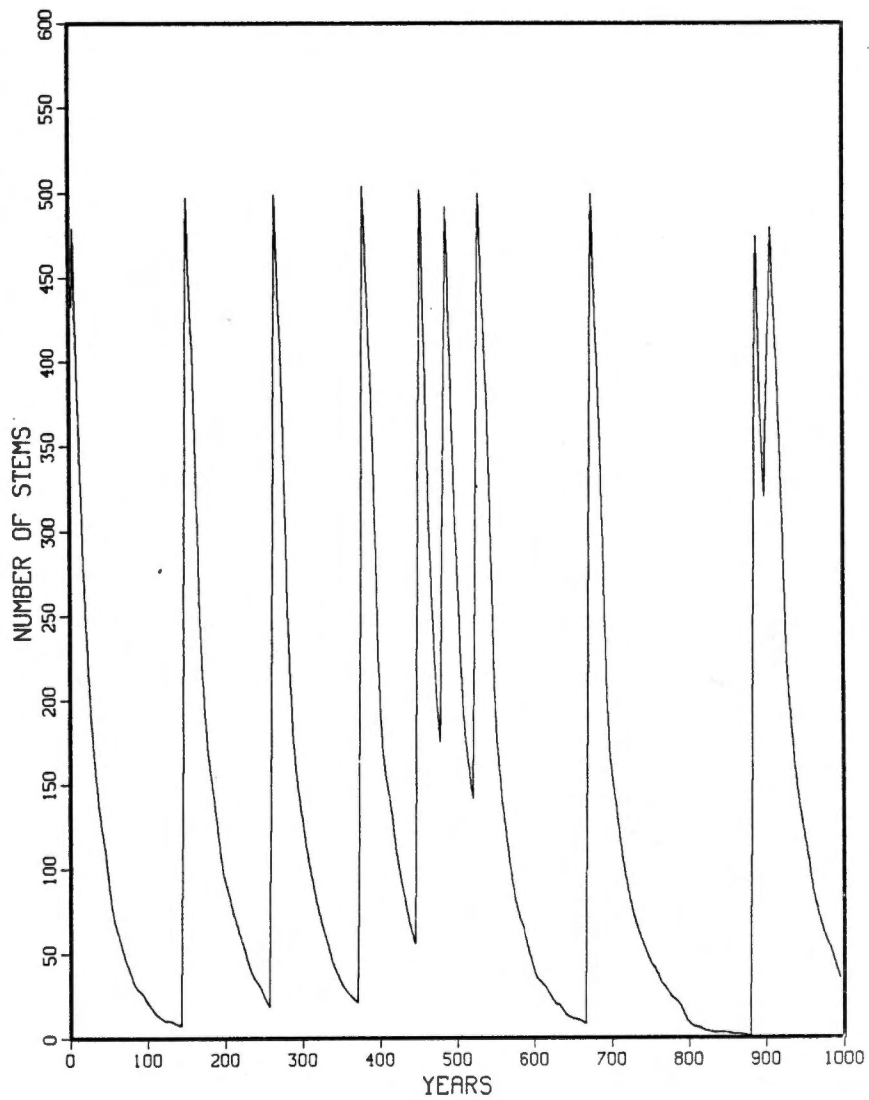


Figure 6.1. Simulated permafrost-free site stem counts (stems)/(1/12 ha) through time. Single plot.

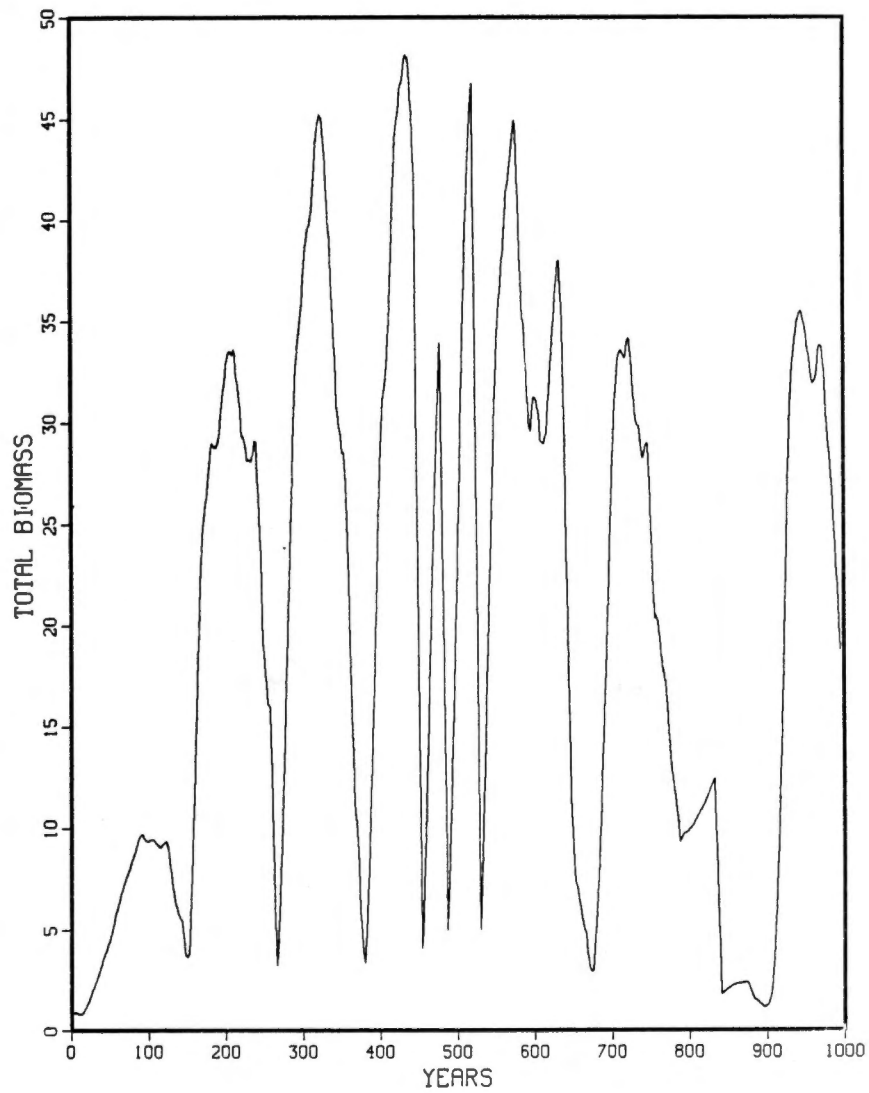


Figure 6.2. Simulated permafrost site total stand biomass (t/ha) through time. Single plot.

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).

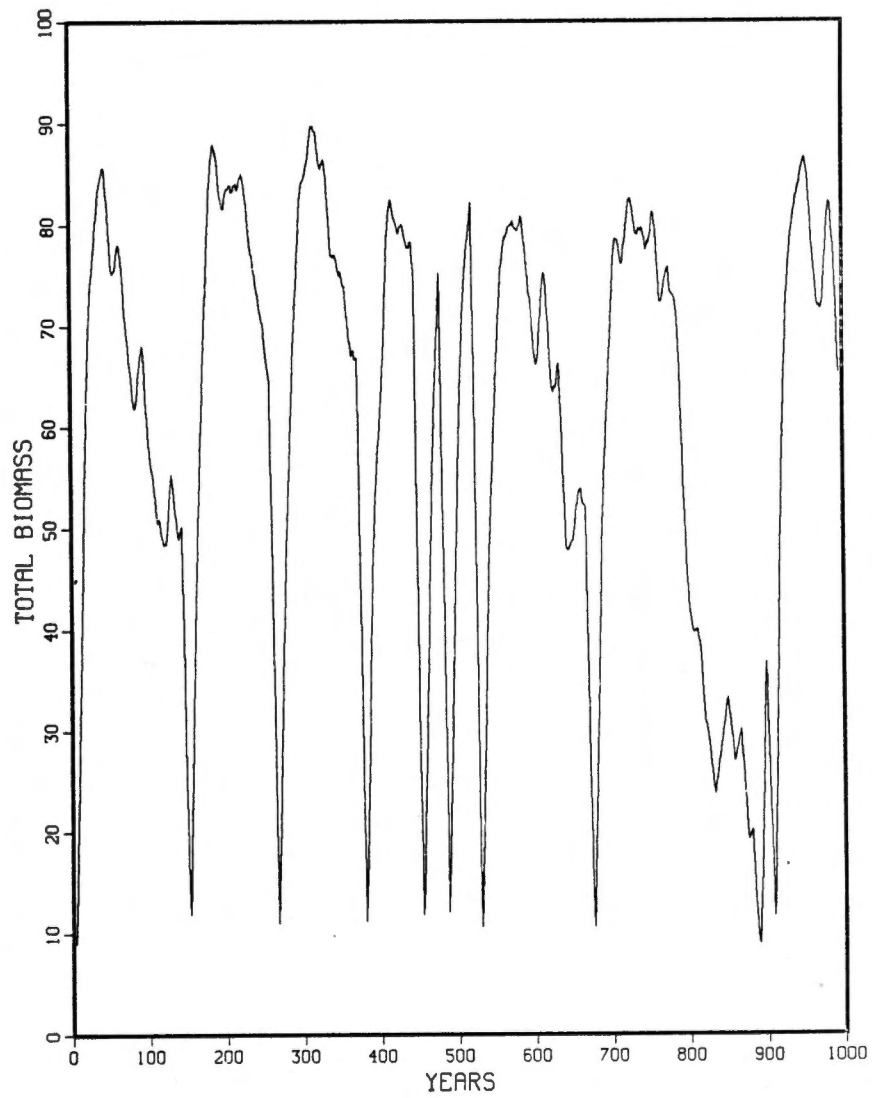


Figure 6.3. Simulated permafrost-free site total stand biomass (t/ha) through time. Single plot.

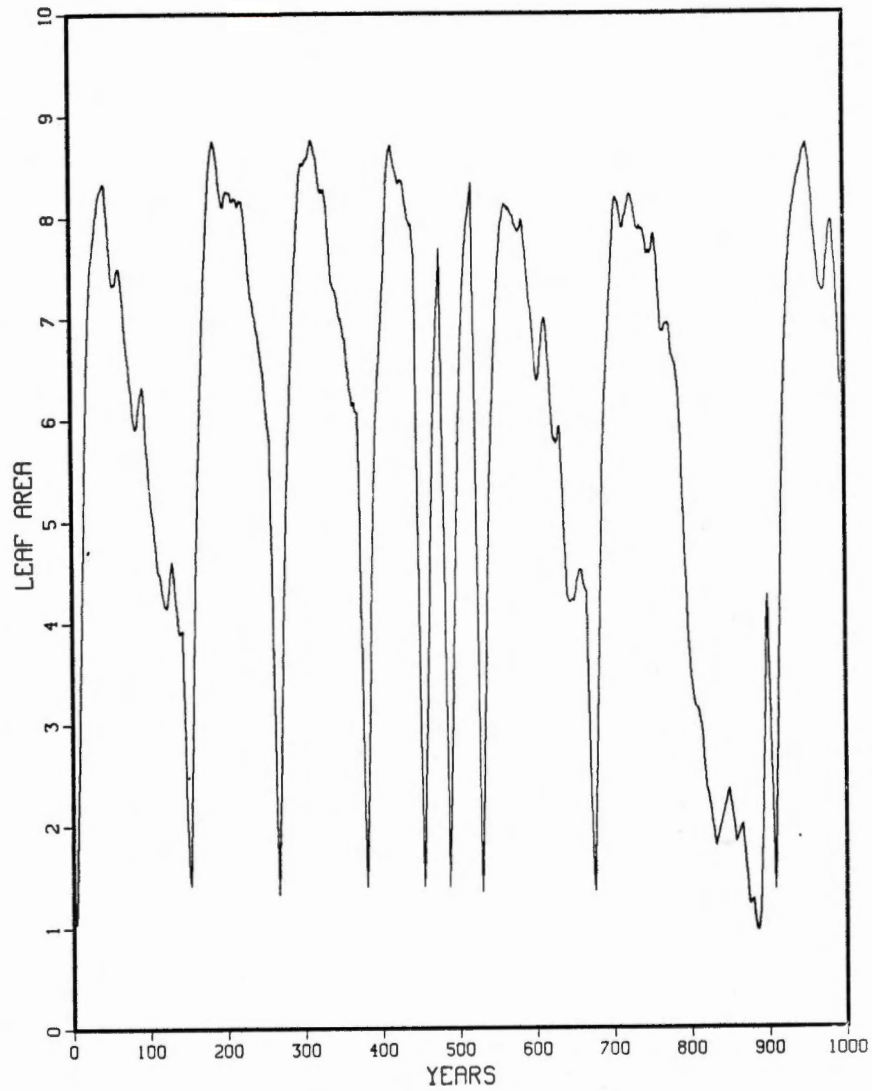


Figure 6.4. Simulated permafrost-free site total leaf area index through time. Single plot.

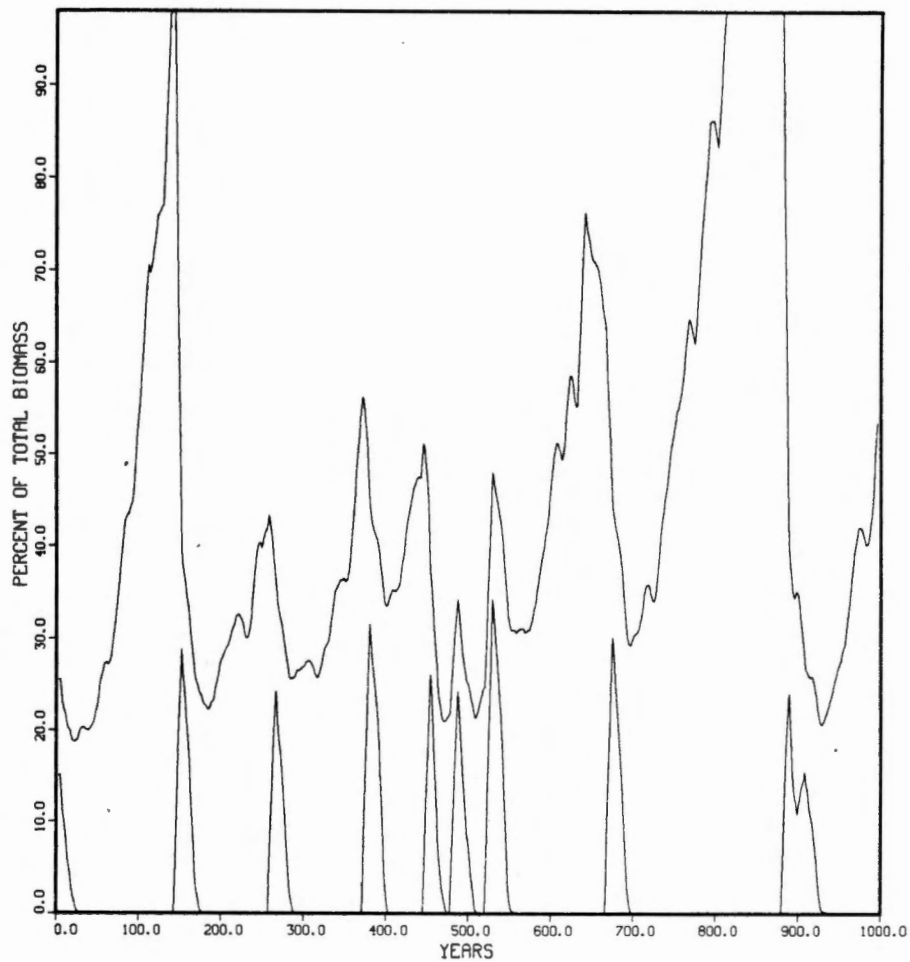


Figure 6.5. Simulated species relative biomass contribution (percent of total) on the permafrost-free site. Area between curves defines percent biomass. Birch: upper area, white spruce: middle area, aspen: lower area. Single plot.

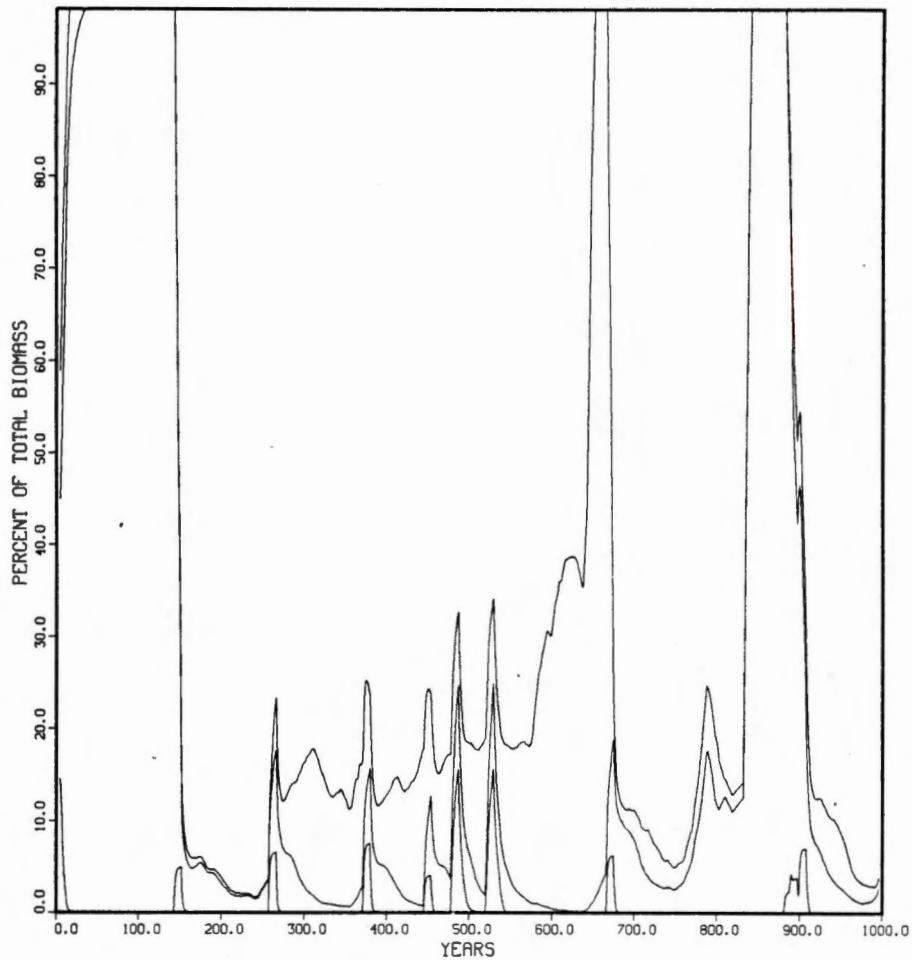


Figure 6.6. Simulated species relative biomass contribution (percent of total) on the permafrost site. Area between curves defines percent biomass. Birch: upper area, white spruce: upper middle area, black spruce: lower middle area, aspen: lower area. Single plot.

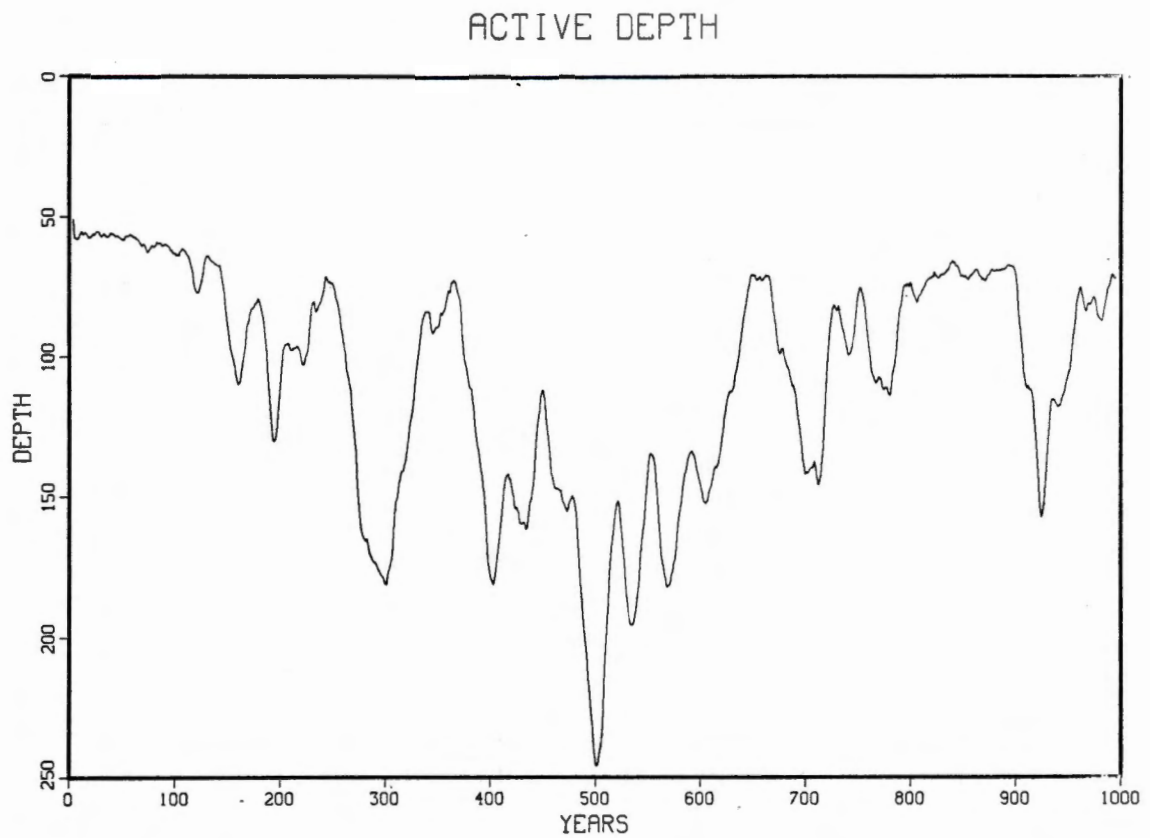


Figure 6.7. Simulated permafrost site active layer depth (cm) through time. Single plot.

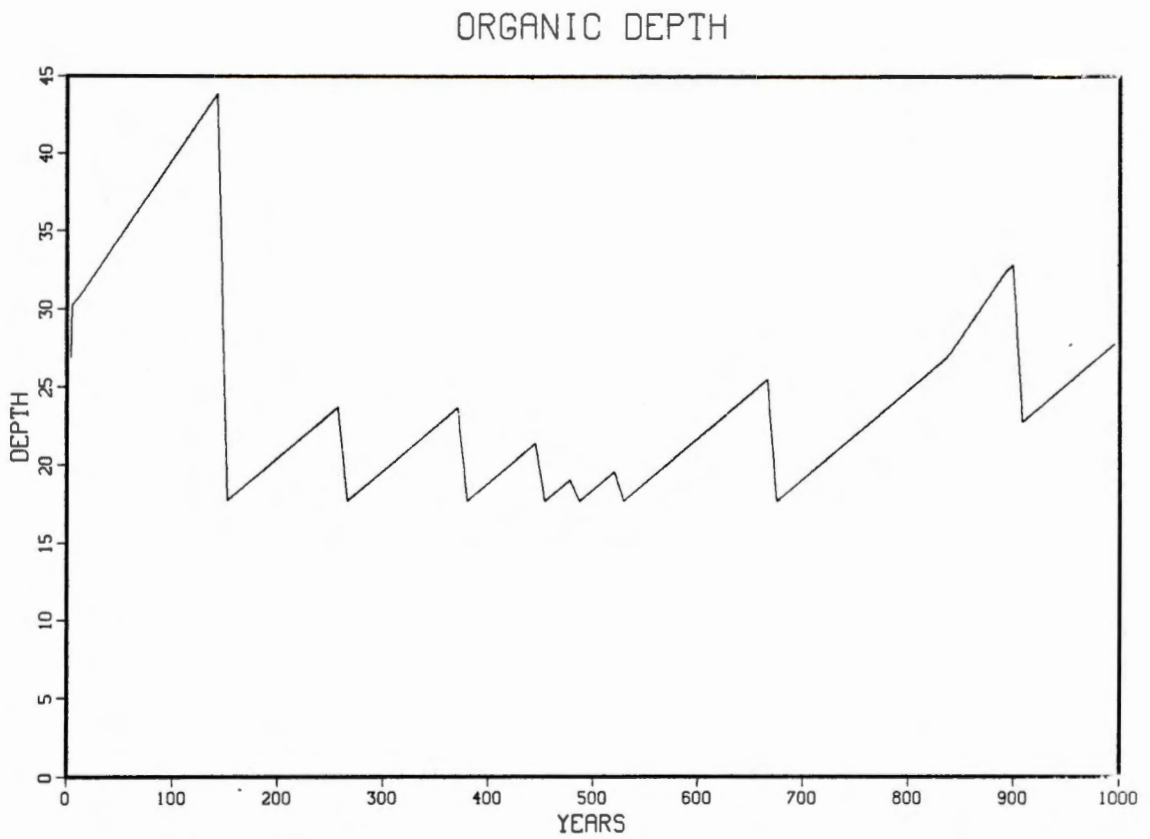


Figure 6.8. Simulated permafrost site organic layer depth (cm) through time. Single plot.

## 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.

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## 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)

| SAS                                          |     |               |                       |                  |                  |
|----------------------------------------------|-----|---------------|-----------------------|------------------|------------------|
| VARIABLE                                     | N   | MEAN          | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>VALUE |
| ----- CLASS=1 NAME=BETULA PAPYRIFERA -----   |     |               |                       |                  |                  |
| BIOM                                         | 168 | 20.41859184   | 13.875952294          | 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      |

| SAS                                          |     |               |                       |                  |                  |
|----------------------------------------------|-----|---------------|-----------------------|------------------|------------------|
| VARIABLE                                     | N   | MEAN          | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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 PAPHYRIFERA -----  |     |               |                       |                  |                  |
| 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      |

## SAS

| VARIABLE                                     | N   | MEAN         | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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 PAPHYRIFERA -----  |     |              |                       |                  |                  |
| 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                |

## SAS

| VARIABLE                 | N   | MEAN         | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>VALUE |
|--------------------------|-----|--------------|-----------------------|------------------|------------------|
| NAME=POPULUS TREMULOIDES |     |              |                       |                  |                  |
| BIOM                     | 113 | 0            | 0                     | 0                | 0                |
| DENSIT                   | 113 | 0            | 0                     | 0                | 0                |
| PERCENT                  | 113 | 0            | 0                     | 0                | 0                |
| 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      |
| 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      |
| NAME=PICEA MARIANA       |     |              |                       |                  |                  |
| BIOM                     | 100 | 0            | 0                     | 0                | 0                |
| DENSIT                   | 100 | 0            | 0                     | 0                | 0                |
| PERCENT                  | 100 | 0            | 0                     | 0                | 0                |
| 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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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      |

## SAS

| VARIABLE                                     | N  | MEAN         | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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 PAPHYRIFERA -----  |    |              |                       |                  |                  |
| 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     |

## SAS

| VARIABLE                                     | N  | MEAN         | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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                |

## SAS

| VARIABLE                                      | N  | MEAN         | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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 | 12.114975422 | 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<br>DEVIATION    | MINIMUM<br>VALUE | MAXIMUM<br>VALUE |
|----------|----|--------------|--------------------------|------------------|------------------|
| -----    |    |              |                          |                  |                  |
|          |    | CLASS=2      | NAME=POPULUS BALSAMIFERA |                  |                  |
| BIOM     | 3  |              |                          |                  |                  |
| 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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>VALUE |
|----------------------------------------------|---|--------------|-----------------------|------------------|------------------|
| ----- CLASS=6 NAME=BETULA PAPYRIFERA -----   |   |              |                       |                  |                  |
| BIOM                                         | 6 | 0.75644979   | 1.197113733           | 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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>VALUE |
|--------------------------|---|---------------|-----------------------|------------------|------------------|
| NAME=POPULUS TREMULOIDES |   |               |                       |                  |                  |
| BIOM                     | 6 | 0             | 0                     | 0                | 0                |
| DENSIT                   | 6 | 0             | 0                     | 0                | 0                |
| PERCENT                  | 6 | 0             | 0                     | 0                | 0                |
| 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      |
| 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       |
| 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      |
| 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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>VALUE |
|--------------------------|-----|---------------|-----------------------|------------------|------------------|
| NAME=PICEA GLAUCA        |     |               |                       |                  |                  |
| CLASS=2                  |     |               |                       |                  |                  |
| BIOM                     | 152 | 2.94760169    | 2.46518655            | 0.04260304       | 8.58962822       |
| DENSIT                   | 152 | 799.5000000   | 221.61708520          | 384.0000000      | 1476.0000000     |
| PERCENT                  | 152 | 8.67546615    | 5.70364185            | 0.34117736       | 17.91565097      |
| NAME=PICEA MARIANA       |     |               |                       |                  |                  |
| CLASS=2                  |     |               |                       |                  |                  |
| BIOM                     | 152 | 1.44566988    | 0.50520120            | 0.74600887       | 3.30019283       |
| DENSIT                   | 152 | 1003.57894737 | 245.13714303          | 600.0000000      | 1644.0000000     |
| PERCENT                  | 152 | 16.50974076   | 31.41828055           | 1.60988708       | 98.72562602      |
| NAME=POPULUS TREMULOIDES |     |               |                       |                  |                  |
| CLASS=2                  |     |               |                       |                  |                  |
| 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       |
| NAME=BETULA PAPHYRIFERA  |     |               |                       |                  |                  |
| CLASS=3                  |     |               |                       |                  |                  |
| 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      |
| NAME=PICEA GLAUCA        |     |               |                       |                  |                  |
| CLASS=3                  |     |               |                       |                  |                  |
| BIOM                     | 121 | 3.63386277    | 3.19603930            | 0.01708793       | 8.99247169       |
| DENSIT                   | 121 | 439.23966942  | 105.78256195          | 228.0000000      | 636.0000000      |
| PERCENT                  | 121 | 8.86207138    | 7.49723900            | 0.27529847       | 25.98763193      |

## SAS

| VARIABLE                 | N   | MEAN         | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>VALUE |
|--------------------------|-----|--------------|-----------------------|------------------|------------------|
| NAME=PICEA MARIANA       |     |              |                       |                  |                  |
| CLASS=3                  |     |              |                       |                  |                  |
| 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      |
| NAME=POPULUS TREMULOIDES |     |              |                       |                  |                  |
| CLASS=3                  |     |              |                       |                  |                  |
| BIOM                     | 121 | 0            | 0                     | 0                | 0                |
| DENSIT                   | 121 | 0            | 0                     | 0                | 0                |
| PERCENT                  | 121 | 0            | 0                     | 0                | 0                |
| NAME=BETULA Papyrifera   |     |              |                       |                  |                  |
| CLASS=4                  |     |              |                       |                  |                  |
| 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      |
| NAME=PICEA GLAUC         |     |              |                       |                  |                  |
| CLASS=4                  |     |              |                       |                  |                  |
| 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      |
| NAME=PICEA MARIANA       |     |              |                       |                  |                  |
| CLASS=4                  |     |              |                       |                  |                  |
| 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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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                |

## SAS

| VARIABLE                                     | N  | MEAN         | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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      |

SAS

| VARIABLE                                     | N  | MEAN        | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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      |

## SAS

| VARIABLE                                     | N  | MEAN        | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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 PAPIRIFERA -----   |    |              |                       |                  |                  |
| 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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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 GLAUC -----         |     |               |                       |                  |                  |
| 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      |

## SAS

| VARIABLE                                     | N   | MEAN          | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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 | 24.777653172  | 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      |

## SAS

| VARIABLE                                     | N   | MEAN         | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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      |

## SAS

| VARIABLE                                     | N   | MEAN         | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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 PAPIRIFERA -----   |     |              |                       |                  |                  |
| 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                |

## SAS

| VARIABLE                                     | N  | MEAN         | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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      |

| SAS                                          |    |              |                       |                  |                  |
|----------------------------------------------|----|--------------|-----------------------|------------------|------------------|
| VARIABLE                                     | N  | MEAN         | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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      |

## SAS

| VARIABLE                                     | N  | MEAN        | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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      |

## SAS

| VARIABLE                 | N  | MEAN         | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>VALUE |
|--------------------------|----|--------------|-----------------------|------------------|------------------|
| NAME=POPULUS TREMULOIDES |    |              |                       |                  |                  |
| BIOM                     | 20 | 0            | 0                     | 0                | 0                |
| DENSIT                   | 20 | 0            | 0                     | 0                | 0                |
| PERCENT                  | 20 | 0            | 0                     | 0                | 0                |
| NAME=BETULA PAPIRIFERA   |    |              |                       |                  |                  |
| 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      |
| 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      |
| 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     |
| 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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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      |

| SAS                                          |     |               |                       |                  |                  |
|----------------------------------------------|-----|---------------|-----------------------|------------------|------------------|
| VARIABLE                                     | N   | MEAN          | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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      |

## SAS

| VARIABLE                                     | N   | MEAN         | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>VALUE |
|--------------------------|-----|--------------|-----------------------|------------------|------------------|
| NAME=POPULUS TREMULOIDES |     |              |                       |                  |                  |
| BIOM                     | 113 | 0            | 0                     | 0                | 0                |
| DENSIT                   | 113 | 0            | 0                     | 0                | 0                |
| PERCENT                  | 113 | 0            | 0                     | 0                | 0                |
| NAME=BETULA PAPYRIFERA   |     |              |                       |                  |                  |
| BIOM                     | 100 | 0            | 0                     | 0                | 0                |
| DENSIT                   | 100 | 0            | 0                     | 0                | 0                |
| PERCENT                  | 100 | 0            | 0                     | 0                | 0                |
| 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      |
| 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      |
| 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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>VALUE |
|----------------------------------------------|----|--------------|-----------------------|------------------|------------------|
| ----- CLASS=6 NAME=BETULA PAPHYRIFERA -----  |    |              |                       |                  |                  |
| 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 PAPHYRIFERA -----  |    |              |                       |                  |                  |
| BIOM                                         | 60 | 0            | 0                     | 0                | 0                |
| DENSIT                                       | 60 | 0            | 0                     | 0                | 0                |
| PERCENT                                      | 60 | 0            | 0                     | 0                | 0                |

## SAS

| VARIABLE                                     | N  | MEAN         | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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 | 32.999632275 | 50.22021506           | 0                | 99.64876785      |

## SAS

| VARIABLE                                     | N | MEAN         | STANDARD<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>VALUE |
|----------------------------------------------|---|--------------|-----------------------|------------------|------------------|
| ----- CLASS=6 NAME=POPULUS TREMULOIDES ----- |   |              |                       |                  |                  |
| BIOM                                         | 7 | 47.12129500  | 124.671122803         | 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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>VALUE |
|--------------------------|---|--------------|-----------------------|------------------|------------------|
| NAME=LARIX LARICINA      |   |              |                       |                  |                  |
| BIOM                     | 4 | 0            | 0                     | 0                | 0                |
| DENSIT                   | 4 | 0            | 0                     | 0                | 0                |
| PERCENT                  | 4 | 0            | 0                     | 0                | 0                |
| 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     |
| NAME=PICEA MARIANA       |   |              |                       |                  |                  |
| BIOM                     | 4 | 0            | 0                     | 0                | 0                |
| DENSIT                   | 4 | 0            | 0                     | 0                | 0                |
| PERCENT                  | 4 | 0            | 0                     | 0                | 0                |
| NAME=POPULUS BALSAMIFERA |   |              |                       |                  |                  |
| BIOM                     | 4 | 0            | 0                     | 0                | 0                |
| DENSIT                   | 4 | 0            | 0                     | 0                | 0                |
| PERCENT                  | 4 | 0            | 0                     | 0                | 0                |
| 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<br>DEVIATION | MINIMUM<br>VALUE      MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE | MAXIMUM<br>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<br>DEVIATION | MINIMUM<br>VALUE      MAXIMUM<br>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.