MODELLING FOREST DEVELOPMENT IN THE MACKENZIE BASIN UNDER A CHANGING CLIMATE

by

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Abstract

The purpose of this study was to explore relationships between baseline climate conditions (1951-1980), and forest composition and productivity, over the Mackenzie Basin at the forest inventory unit level, for use in the development of a forest productivity model. The Mackenzie Basin Forest Productivity model (MBFP model) was then constructed to project the climate-related forest attributes through climate change conditions, as predicted by global circulation models (GCMs).

The tree species studied were black and white spruce *(Picea mariana* (Mill.) B.S.P. and *Picea glauca* (Moench) Voss.), jack pine (*Pinus banksiana* Lamb.), lodgepole pine (*Pinus contorta* Dougl.) trembling aspen (*Populus tremuloides* Michx.), and paper birch (*Betula papyrifera* Marsh.). Only 18% of the area within the Mackenzie Basin had adequate forest inventory information for use in building the climate relationships and the MBFP model. The aggregation method used for multiple stand records within inventory units was described, with the transfer of information across scales recognized as an area of concern. Each species was assigned to age groups; productivities in the first three age groups were related to the baseline climate conditions (1951-80) using multiple linear regression techniques at the inventory unit level. The relative proportions of each species in each inventory unit were also related to the baseline climate conditions (1951-80) in a similar manner. The relationships for species productivity varied in R^2 values from 0.09 ($MSE_e^{1/2}$ 5.83m^3/ha) to 0.48 ($MSE_e^{1/2}$ 4.04 m^3/ha). The relationships for species' relative proportions in inventory units varied in R^2 values from 0.14 ($MSE_e^{1/2}$ 0.03) to 0.41 ($MSE_e^{1/2}$ 0.16).

The model was built using the GRASS GIS environment supported on the Linux operating system. Productivity, mortality (through surrounding conditions and fire), and establishment were represented in relation to climate in the model. The approaches used in modelling these processes were described and source code provided. Suggestions for calibrating the model to baseline climates provided by

various Global Circulation Models (GCMs) were made and a design for a sensitivity analysis was given. Results from running the model were not provided due to limitations reached in the fire module imposed by the modelling environment. Overcoming these limitations was considered to be beyond the scope of this research.

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Chapter 1. Introduction

1.1 Background.

The present distribution and composition of forested land is, in part, a result of past climate influences. Continental forest regions are a result of widespread common favorable climatic conditions for various activities, including species availability for invasion and establishment, and conducive growing conditions. Establishment and disruption of individual forest stands occur through many natural and anthropogenic processes. Climate change has the potential to alter the frequency of forest-level disturbances (such as fire and insect attack), which will cause a subsequent change in the area and distribution of forested land, as different species, compositions and locations may be favored in the newly configured system. It is through an understanding of interconnected feedback relationships between forest components and climate that forest predictions under climate change can be addressed.

The global climate change concept is widely accepted, with the present global temperature increase expected to continue (Hansen *et al.*, 1987; IPCC, 1990; Pollard, 1985). The causes and rates of past and present climate changes remain largely unknown; however, their importance to biotic systems are increasingly recognized. The expectation is that change in climate will not be uniform over the planet's surface, with the middle to high latitudes (23° to 70°) being affected sooner and more intensely than the tropics (Kauppi and Posch, 1985; Woodwell, 1989). As changes occur, the ability of plants to survive will be affected, and species composition within communities will change (Roberts, 1989a). The northern ecosystems have adapted to a low net energy input, and it is thought that they will be more sensitive than other systems to a change in the timing and magnitude of inputs received (Roots, 1989).

The present growth rates, composition, longevity, and total biomass of northern tree species vary with climate conditions (Jozsa and Powell, 1987). As climate changes, the composition of the boreal forests will also change; however, there is no body of ecological theory that can predict the outcome of competition at a specified time or place. This generally forces forest modelling to be conducted at either very fine sub-stand to stand scales (with a limited number of species, a large list of rules concerning competition, and detailed input) or at much coarser continental and global scales (with general assumptions addressing the major requirements for the presence of tree species). A model scaled between these two extremes may be useful for looking at subcontinental forest systems, and the effects of global climate change on forest attributes such as species composition, productivity, and forest location. Relationships between climate parameters and forest attributes could be used in such a model to provide empirical estimates of the forest response.

The Mackenzie Basin Impact Study (MBIS) is a six year project to assess the potential implications of a warmer climate for the Mackenzie Watershed (Appendix 1). This northern region is well suited for climate change research, as it is expected to be affected sooner and more intensely, than many other areas of the world. The forestry component of this collaborative work involves basin-wide predictions for fire hazard, insect attack and forest productivity response to climate change through the use of the Mackenzie Basin Forest Productivity model (MBFP model). The work presented here describes the development of a methodology for forest productivity predictions related to climate parameters, including the structural framework for the MBFP model.

1.2 Research Objectives

The major objective of this research was to develop a procedure for building relationships between the present forest inventory and climate parameters over a large geographic area. To support this large scale work, a method for scaling up the available stand-level forest inventory needed to be developed.

The specific objectives were:

1. to refine the national and provincial forest stand-level inventories data to a scale at which each unique geographical location holds a single series of inventory observations;
2. to build relationships between these modified forest inventory records and the 1951-80 baseline climate parameters; and
3. to develop an approach to modelling changes to forest composition and productivity in relation to climate over a large scale using the Geographic Resources Analysis Support System (GRASS) Geographic Information System (GIS).

1.3 Overview of Thesis

The second chapter of this thesis contains a literature review introducing global climate change theory, and the possible responses of boreal forest ecosystems to climate change. Chapter 3 contains an outline of the methods used for refining and compressing the stand-level forest inventory, selecting climate parameters, and building relationships between the selected climate parameters and forest species composition and productivity. The modelling approach used to represent forest dynamics over a large scale and a discussion of the components of a forest-level model are included in Chapter 4. Chapter 5 contains a general discussion, conclusions, and recommendations regarding the different alternatives available for this type of work, and their future potential.

Chapter 2. Literature Review

2.1 Global Climate Change

The concept of global climate change is widely accepted and has been frequently noted in the fossil records. However, the cause and rate of change, both past and present, remain largely unknown. Recent warming has promoted the concept of "the greenhouse-effect", which is easily understood, and has scientific support from measured increases of atmospheric carbon dioxide (CO_2) concentration. This section will examine the causal factors of climate change and the predictions made about our global climatic future.

The earth's climate is continually changing in character, alternating between ice ages and warmer periods with no defined base condition. Current theories of climate change are often tested against climate data recorded at an earlier stage in the earth's cycle. Verification of the data used, and differences in its interpretation among researchers cause the validity of these tests to be questioned, as they are both predicting, and testing at different stages in a cycle. Information, referred to as proxy data (from more than two thousand years ago) are retrieved from ice cores, ocean sediments, fossils, tree rings, and similar sources. Using this information, it has been determined that a minor change in the average global temperature can result in extreme weather pattern variation and ecosystem shifts (Sargent, 1988). The earth's orbital characteristics are considered to be the driving force of past, long term climate cycles. From deep-sea cores, it appears that the change between glacial periods and warmer global temperatures (like today) appear gradually over about a 100,000 year cycle. However, planktonic organisms in North Atlantic Ocean deep-sea cores reflect an abrupt end to the cold period, followed by an interrupted warming period (Broecker, 1987). This illustrates the importance of data source and interpretation, as opposing results are difficult to decipher. There have been nine mass extinctions recorded on earth since higher life forms appeared 600 million years ago (Harrington, 1987). The reasons for these are not fully understood, but changes in climate conditions are indicated.

Climate is generally recognized as the primary factor controlling ecosystems (Melillo *et al.*, 1990). It consists of a series of feedback systems; systems where factors that produce a result are themselves modified by that result (Perry *et al.*, 1991). Solar radiation, temperature, humidity, precipitation, and wind directly affect the ecosystem, with these factors representing just a few of the climate's components. Change in any one of these factors is expected to disturb the balance of the others within the feedback system.

A 0.5 °C rise in mean global temperature has occurred over the last 100 years (Pocklington, 1992; Roberts, 1989b) and temperature is expected to continue to rise and cause disruption to global feedback systems (Folland *et al.*, 1990). It is the accumulation of infra-red absorptive gases in the atmosphere that is thought to be causing the warming by allowing short-wave radiation emitted from the sun to enter the atmosphere, but blocking transmission of long-wave radiation emitted from the earth's surface back through the atmosphere, thus trapping energy. As a result, global temperature increases.

Global warming is affected by the carbon feedback system, with the largest amount of the earth's carbon stored in the ocean. The yearly carbon flux between the ocean and atmosphere, and between the land and atmosphere, are similar in magnitude. An increase in the amount of carbon released from land storage (through the burning of fossil fuels, and reduction of carbon-trapping land types through changes in land use) will result in a change to the total carbon released from the earth's surface to the atmosphere, thus enhancing the emissions of greenhouse gases (Perry *et al.*, 1991). The concentration of atmospheric CO_2 varies, depending on how the carbon is cycled in the global ecosystem (Hoffman and Wells, 1987a,b). Warmer temperatures that result from higher concentrations of greenhouse gases are expected to increase the rate of organic matter decay, without an equal rate of increase in gross photosynthesis, thus changing the balance of carbon release to carbon fixation, and resulting in positive feedback (Larsen, 1989).

The major known, radiatively important atmospheric constituents are: clouds, aerosol, water vapor, CO_2, methane (CH_4), ozone (O_3), nitrous oxide (N_2O), sulphur oxide (SO_x), and chlorofluorocarbons (CFC's) (Bolin *et al.*, 1986; Dickinson, 1989; Mendelsohn and Rosenberg, 1994; Rizzo, 1988). Each gas contributes to the greenhouse effect differently, depending on the individual wavelength at which it absorbs radiation, whether other gases absorb at that same wavelength (and how strongly), its concentration, and the absorptive strength per molecule. An example of this differential impact is seen in the difference between one molecule of CFC-12 (dichlorodifluoromethane) and one molecule of CO_2, as CFC-12 absorbs 10^4 times more long-wave radiation than an equivalent amount of CO_2 (Mitchell, 1989).

The global atmospheric concentration of CO_2 was measured in 1958 at 315 ppm. The concentration in 1984 was 345 ppm, and the pre-industrial concentration (based on data from air occluded in ice cores (Neftel *et al.*, 1985)) is estimated at 280 +/- 5 ppm. The trace greenhouse gases are increasing in concentration, which is due to the combustion of fossil fuels, use of fertilizers, synthesis of chemical compounds, and large changes in land use (Hansen *et al.*, 1987; Hoffman and Wells, 1987a). Considerable variability in the data records makes it difficult to conclude that the recent rise in global temperature is due to an increase in trace gases. Predictions of the rate of temperature change are likely to become more reliable as assumptions are refined on trace gas concentrations, sensitivity of the climate, and the thermal inertia of the oceans.

The present atmospheric CO_2 concentration is expected to double by the middle of the next century

(Harrington, 1987; Anonymous, 1989), resulting in a 1.5 to 4.5 °C increase in mean annual temperature (Bolin *et al.*, 1986; Kauppi and Posh, 1988; Mendelsohn and Rosenberg, 1994; Woodwell, 1989). This will occur if the 4.5% annual rate of increase in CO_2 production and the 55% retention of the emissions by the atmosphere continues (Pollard, 1985). However, many of the greenhouse gases have a long life in the atmosphere, making it difficult to calculate concentration due to individual accumulation and dispersion rates (Hoffman and Wells, 1987a).

The increases in temperature measured to date are no greater than that caused by natural year-to-year variability, according to Kerr (1991), but there is a clear trend (Skinner, 1995). The global temperature increase is expected to exceed the natural variability during the 1990's, and continue rising rapidly (Hansen *et al.*, 1987). Record temperatures have been measured in recent years, with 1993 as the tenth warmest year on record, 1994 as the sixth warmest year, and all indications point to 1995 being one of the warmest years as well (Gullett and Skinner, 1992; Skinner, 1995; Wilson and Hansen, 1994). Unlike the previous record breaking years, there was no contribution from the El Niño effect (Kerr, 1991). After a ten year study of global temperature trends, Jones and Wigley (1990) described the global climate as highly variable over periods of decades or less, with a general warming trend for the past century. This trend of rising global temperature is no longer in question, but the rate of increase and causes are (Folland *et al.*, 1990; Jones and Wigley, 1990).

To help predict global temperature and climate, computer models have been developed. Of these, Global Circulation Models (GCM's) are the most widely used. These models are currently unable to reproduce historical changes in climate, as only parts of the system being modelled are known in detail; however, the versatile GCM-based scenarios are still preferred to alternative methods (Skiles, 1995). Better known global circulation models include the Goddard Institute for Space Studies (GISS) model, the Oregon State University (OSU) model, and the Canadian Climate Center (CCC) model.

Most climate processes are used as individual variables in the models and these variables (both in number and type) are what give the models their unique character. It is recommended that impact studies use the results from several models, as the predictive models cannot be quantitatively validated, and each model has a degree of subjectivity that should be countered through comparison (Skiles, 1995; Stuart and Judge, 1991).

Global climate changes are not expected to be uniform over the planet. The greatest temperature change is anticipated at high latitudes in the winter, and the smallest temperature change is anticipated over sea ice in the summer. The warming is expected to affect the northern hemisphere's middle to high latitudes (23 to 70 degrees) sooner, and more intensely, than the tropics (Kauppi and Posh, 1985; Woodwell, 1989), with the local CO_2 concentration rising at a slightly higher rate in the north. Regional temperature increase is predicted consistently by GCM's to be highest in the Arctic (Brown and Walsh, 1986; Emanuel *et al.*, 1985).

GCM's typically project climate changes to a spatial resolution of 300-1000 km^2. The scale of these models cannot be reduced for any specific geographical area; they are reliable only at the global and continental level. GCM's are limited by their inability to model cloud cover which directly influences the earth-atmosphere feedback loop by reflecting of incoming solar radiation and trapping heat in the lower layer of the atmosphere. Topography is rarely included (*i.e.*, mountain ranges, plateaus and large lake influences are left out) causing major regional inaccuracies. For example, in a recent paper by Stuart and Judge (1991), GCM estimates were used for the Mackenzie valley area. Large errors occurred in the attempts to reproduce general temperature and precipitation patterns of the valley. However, GCM's continue to be the best available method for exploring and predicting the complex systems affecting climate.

The response to an increase in temperature in the Arctic is predicted to be related to two positive feedback systems. The first involves ice and snow surfaces, which would melt sooner and return later in the warmer conditions. The loss of these high albedo (highly reflective) surfaces will promote absorption of solar radiation and increase temperature further. Both air and surface changes to sea-ice cover are very important, as the ice generally persists for several months longer into the summer than snow and ice on the land. The second feedback system is related to the stable atmosphere at high latitudes (where temperature decreases with altitude more slowly than at lower latitudes). This is accompanied by low convective coupling between the atmosphere and earth's surface, so that temperature differences are largest at the surface in response to changes in surface heating (which result from exposure to solar radiation (Bonan *et al.*, 1995; Dickinson, 1989). Both of these feedback systems affect surface temperatures, which in turn affect vegetation.

Vegetation in the north will be physiologically stressed by higher temperatures and lower soil moisture, although water use efficiency is expected to increase (Pastor and Post, 1988). The frequency of pests and fire, are also expected to increase, given milder winters and warmer summers, causing further stress to the plants (Flannigan and VanWagner, 1991; Perry, 1991; Pollard, 1989).

Vegetation zones may shift from their present distribution by hundreds of kilometers per degree Celsius change in global temperature. The rate of climate change is predicted to be much faster than the ability of most of the present climax species to adapt. The only plant species expected to migrate fast enough to keep pace with the rate of climate change are the quick colonizers (Woodwell, 1989). Soil development may further restrict species migration with climate change, because soil forming processes occur over a longer time frame than the expected climate changes (Pennington, 1986).

There is a group of researchers that believe "the change" is not happening, or that human intervention has not been the cause. "... if we don't know what caused the climatic changes and fluctuations of the past, then it is unlikely we will be any wiser in our assessments or speculation about the nature of future changes and fluctuations in the climate " (Coughlan and Nyenzi, 1991). The observed rise in temperature over the past 130 years has not clearly followed the progressive use of fossil fuel. The greatest temperature increase recorded was from 1860 to 1940, and during this period there was only 20% of the present total industrial emissions (Pocklington, 1992). These figures do not support industrial carbon release as the cause of climate change. However, the time period does parallel the deforestation and change in land use of newly colonized lands, such as North and South America, and New Zealand, which would have reduced the areas net carbon fixation abilities, and released CO_2 through forest removal.

2.2 Limiting Environmental Factors of the Boreal Forest Ecosystem

The northern boreal region is limited by edaphic and climatic conditions with strong seasonal variation characterizing the ecosystem. Short, moderately warm, moist summers are followed by long, cold, dry winters. The northern and southern boreal forest boundaries of North America are a result of various environmental factors, such as: summer temperature, short growing season (May to October - Larsen, 1980), character of solar radiation and its effect on photosynthesis and germination, desiccating winds, low humidity and resulting fire frequency, Arctic and Pacific air mass position during the growing season, water relations, snow cover, permafrost and resulting thickness of soil active layer, and nutrient availability. The relative importance of these elements is widely disputed, but each determines a component of the ecosystem, and plays a part in its functioning. The individual environmental factors are interconnected, creating feedback, as well as direct reaction to change (Black and Bliss, 1980; Bonan, 1988; Bonan et al., 1995; Bonan and Shugart, 1989; Bryson, 1966; Hopkins, 1959; Kuusela, 1990; Kwang and Gan, 1995; Larsen, 1980 and 1989; Payette *et al.*, 1989;

Singh and Higginbotham, 1987; Tuhkanen, 1984). Major associations between physical and biotic factors are described in this section to express the complexity of the forest system and its species.

Six thousand years ago the north coast of Canada was forested (Diaz and Andrews, 1989; Spear, 1983). The boreal zone has moved since then, as climate change forced plant species to migrate south (Sargent, 1988; Singh and Wheaton, 1991; Spear, 1983). Success of each migrant species is related to seed dispersal, quick establishment, phenotypic plasticity (ability to adapt to conditions), and early sexual maturation (Payette *et al.*, 1989). Tree species migrated across latitudes, incurring further selection through changes in day length, seasonal pattern, and winter dormancy requirements. The present boreal northern tree-line across mainland Canada corresponds relatively well to the 10°C mean July isotherm. The northern limit of the boreal forest is roughly bounded with the 13°C mean July isotherm. These two mean July isotherms also define the zone of the Arctic Front mean July position (Bryson, 1966; Edlund, 1986). Low air temperature during the growing season slows the rate of photosynthesis, and temperatures below this 10°C level on the Canadian mainland are not adequate for tree success, although tree islands in the far north do survive and perpetuate through asexual reproduction (Edlund, 1986; Hopkins, 1959; Kay, 1978).

Moisture and temperature regimes are established primarily by the amount and intensity of solar radiation received (Larsen, 1989; Wheaton *et al.*, 1987). With dramatic changes in the photoperiod throughout the year, large fluctuations in surface heat and winds occur. Air temperature and atmospheric pressure changes also occur throughout the year which affect air currents, cloud cover, and admission of solar radiation (Anonymous, 1972). Changes to the amount and pattern of radiation received by an ecosystem will directly affect its productivity, and indirectly affect its climate. The relative simplicity and hardiness of the remaining northern flora is thought to be a result of the species migrations, which occurred in response to the major fluctuations in the earth's climate (Larsen, 1980;

Solomon, 1989).

The boreal forest is a mixture of a few coniferous and deciduous species, with site-specific associations and compositions. The most frost resistant conifers are black and white spruce *(Picea mariana* (Mill.) B.S.P. and *Picea glauca* (Moench) Voss.), and tamarack (*Larix laricina* (Du Roi) K. Koch). They survive in areas where the ground may be frozen for five to eight months, and continuous permafrost remains below the active layer of soil (Fowells, 1975). All the species in the north have wide ranges over Canada, and are able to grow on many types of soil, which relates back to their migrational origins.

Associations containing black and white spruce, balsam fir (*Abies balsamea*), and trembling aspen (*Populus temuloides* Michx.) are common in the present boreal forest, with paper birch (*Betula papyrifera* Marsh.) associated with all of the above species. Tamarack occurs frequently with both spruce types, while jack pine (*Pinus banksiana* Lamb.) associates with white spruce, and is found in a variety of other mixtures. Black spruce can occasionally be found in the southwestern boreal forest with subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) and lodgepole pine (*Pinus contorta* Dougl.) (Fowells, 1975; Hosie, 1979). Each boreal tree species has particular attributes which can favour or exclude them from an establishment opportunity or a mortality event. These attributes include the timing and mechanism of seed dispersal, preferred soil moisture and nutrient regimes, tolerance to shade, preferred elevation and slope position, aspect, and soil medium.[1] Different associations will evolve as sites alter and species migrate during climate change.

White spruce has been the major tree species in the Mackenzie Delta forest-tundra ecotone for at least

[1] For a more complete description of the silvics of various species, refer to Fowells (1975), or Hosie (1979).

the last 5500 years (Spear, 1983). It spread at a rate of 2000 kilometers per 1000 years from southern Alberta to the Mackenzie Delta after the end of the Wisconsin glaciation, 9000 years ago (Ritchie and MacDonald, 1986). This rapid rate of spread (several times greater than any previously recorded for spruce) is attributed to the light, winged seed that is released in autumn to early winter and is able to travel over frozen ground and snow. The western interior region aided the migratory movement by having relatively flat open terrain with strong surface winds at that time of the year. In the recent climate warming (since the little ice age of the 1850's), the northern forest limit has significantly expanded, with white spruce increasing in regeneration vigor, density, biomass productivity, and occupying higher altitude areas (Payette and Filion, 1985). The fluctuation in climate conditions cause variations in species composition, growth rates, longevity and total biomass (Jozsa and Powell, 1987).

The northern-most black spruce populations are fragmented relics of forests established in a warmer period. Regeneration is rare in the forest-tundra ecotone; the trees do not produce viable pollen or seeds, there is no buried seed store, and juveniles are generated episodically by asexual means, mostly by layering (Elliott, 1979; Ritchie and MacDonald, 1986). Similar regeneration patterns have also been observed for white spruce (Black and Bliss, 1980).

Spruce stand structure and dynamics have been studied throughout the boreal region (Kuusela, 1990). Climax communities have been found to have only a small proportion of old trees (250 years plus) as they are replaced over time (Dyrenkov, 1981). White spruce has the highest commercial value of any of the northern tree species and has been the subject of the most research. Black spruce is usually found in uneven-aged stands, unless there is a history of disturbance such as fire or clear cutting (Ung and Ouellet, 1991). Regeneration of harvested sites has been successful through the release of layers and suppressed stems (most of which respond). These harvested sites are productive, with species decay levels no greater than that found in natural seed-originated stands (Paquin and Doucet, 1992a,b).

The northern-most coniferous forests are slow growing, with a mean annual volume increment one-fifth of that found in southern stands of the same species (Havas, 1981). Woody plants experience high respiration costs in the far north, resulting in short, sparse trees which eventually give way to tundra. The thin stands allow more light to reach the forest floor, giving ground vegetation a greater productivity than that typically found in southern stands (Havas, 1981). As the humus layer from litter fall and ground vegetation increases in thickness, trees and seedlings are separated from the mineral soil. This causes regeneration and growth to decrease, and low productivity to be perpetuated (Havas, 1981). Other stress factors determining the tree-line are low soil nitrogen availability, slow nutrient cycling, and limited energy flow (Pastor *et al.*, 1987).

Physical conditions such as topography and soil, which limit tree species establishment and success in the north, are the result of climatological and geological history. The Mackenzie Basin has been divided into three geologic regions in past studies: the Western Cordillera (sedimentary rock with metamorphosed igneous rocks within the strata), the Interior Platform (beds of sedimentary rocks of varying ages), and the Canadian Shield (igneous granites and gneisses with bands of volcanic and sedimentary rocks) (Anonymous, 1972). Soils vary greatly throughout the basin and include sandy outwash, till, loam and lacustrine soils. In regions of continuous coniferous forest, high precipitation, and low evaporation rates lead to podzolization and acidity in the soils (Larsen, 1989).

The forest floor vegetative layer is a very important component of stand productivity. Structural dynamics, as well as nutrient, moisture, and energy flows, are all dependent on the vegetative layer, which is generally comprised of several plant types. Lichens are important members due to their low conductivity and highly reflective surfaces. Mosses replace lichens in moist shaded woods; they immobilize water and nutrients, and are controlling factors in boreal forest dynamics (Bonan and Shugart, 1989). In colder conditions, nitrogen, potassium, and phosphate are stored increasingly by moss, and in mid- to late-successional stages of the boreal forest, moss is an effective competitor with trees for these nutrients (Van Cleve and Viereck, 1981).

In boreal areas, high water content in the soil results in slow organic matter decomposition, causing accumulation over time. This is an important factor in the water, carbon, and nutrient cycles of the north (Bonan and Shugart, 1989). Soil moisture, thaw, and drainage vary with the seasonal snow melt, topography, and permafrost. The vegetation patterns in part reflect these moisture conditions, with the northern forest limit paralleling the southern permafrost boundary (Larsen, 1980).

The permafrost of the Mackenzie Basin originated during the Pleistocene, with a few areas remaining from the early Wisconsin Ice Age, more than 40,000 years ago. Conceptual linkages between permafrost and the boreal ecosystem are well understood, with slow changes to the ice-rich materials due to the thermal inertia they require. Insulating ground-cover in the form of forest canopy, organic matter, and snow is very important to thermal dynamics. It allows higher ground temperatures to be maintained over the winter season, and cooler temperatures (due to the reflected solar radiation and the cooling effect of evaporation) to occur over the short summers. The discontinuous southern boundary of the permafrost is found on poorly-drained northern and eastern exposures and exists in a delicate equilibrium. Long-term changes in temperature will affect the location of this boundary, as well as the processes of ice wedge cracking, frost heave, mass movements, and slope instability (Bonan and Shugart, 1989; Bonan *et al.*, 1990; Crampton, 1974; Kwong and Gan, 1995; Larsen, 1980; Smith, 1986).

The frequency and intensity of major disturbances to the forest are important for anticipating future climate change impacts on forest dynamics. Insect infestations occur commonly, with outbreaks of defoliating insects killing or damaging forests. In turn, the damaged forests become more susceptible to fire, as the dead trees dry to become optimal fuel (Bonan and Shugart, 1989). Recurring wildfires lead to a mosaic of vegetation stages within the forested landscape, and are the main cause of young forests. Frequency of fire ranges from 50 to 200 years, with rare moist, protected sites burning approximately every 500 years (Payette, 1992). The intensity of the burn, and the extent of the loss of forest floor, determine the type of regeneration. Nutrient cycling is changed due to temporary assart effects (Holling, 1992), and the successional trajectory is restarted with a new composition of plant species. No single regeneration sequence has been established for the boreal region, as areas differ in aspect, permafrost and active soil layer (active rooting zone). The seed bank is typically of low viability, with tree species having other reproductive strategies such as serotinous cones and vegetative reproduction (Bonan and Shugart, 1989; Van Cleve and Viereck, 1981). Factors such as local site quality and tree seed availability can greatly influence the speed and direction of forest recovery.

2.3 Determining Possible Impacts of Climate Change on Trees and Forests

Climate change estimates for the boreal region are made by global climate models. The boreal region is predicted to have a higher temperature, a small increase in precipitation, and a possible increase in productivity from the increased CO_2 concentration (Botkin, 1990; Singh and Powell, 1986; Wheaton *et. al.*, 1987). As changes occur, the ability of plants to survive will be affected. Northern ecosystems have adapted to a low net energy input. Therefore, they will be more sensitive than other systems to a change in the timing and magnitude of energy received (Roots, 1989). Longer, warmer growing seasons will increase an area's total productivity potential, but the composition of the surviving community is not known (Edlund, 1986; Pastor and Post, 1988; Singh and Wheaton, 1991;

Wheaton *et al.*, 1988).

Under new climate conditions, a group of species which share certain traits will have particular advantages relative to other species. These differences in species fitness will result in a change of species composition (Higginbotham *et al.*, 1985; Kramer and Sionit, 1987; Kuusela, 1990). Unfortunately there is no ecological theory that can predict the outcome of competition as the processes involved are inherently unpredictable at any one specified time or place. Hence, forest models which incorporate species competition work with probabilities and distributions rather than deterministic outcomes (Solomon, 1988).

When forest models include climate relationships or requirements for specific species, they are dependent on the accuracy of the climate data. Regional climate change predictions are not possible with the present coarse data and theories, which means that future climate impacts on specific ecosystems cannot be estimated with any confidence (Bolin *et al.*, 1986; Bugmann and Martin, 1995).

Forests directly affect climate at the global scale by altering the earth's albedo, terrestrial hydrology, and atmospheric CO_2 concentration (Graham, *et al.*, 1990; Kerz *et al.*, 1995; Roots, 1989). The local climate is affected as well, with temperature, humidity, and solar radiation being altered. Terrestrial regions have a theoretical maximum tree productivity which can only be achieved if the most efficient competitors for local resources reach their optimum growth (Solomon and West, 1985). When climate fluctuates, the balance is upset and readjustments lag, causing a period of lower productivity and carbon fixation (Kuusela, 1990; Layser, 1980; Pastor and Post, 1988). As the global climate changes, it will be affected by the forests through feedbacks (such as reduced carbon fixation rates) which are poorly represented in current climate models (Mendelsohn and Rosenberg, 1994). These effects will be significant, as forests are a major agent of global photosynthesis and carbon fixation (D'Arrrigo *et al.*, 1987; Eamus and Jarvis, 1989).

There are many sources of uncertainty found in forest and climate simulation experiments. Current experiments performed on growth in CO_2 enriched environments are of questionable predictive value. Conditions such as light, temperature, and soil moisture vary significantly between experiments, and significantly from the natural forests, which makes extrapolation to future field conditions more difficult. Tests are generally run on single tree species rather than on mixed species, the specimens used are generally quite young, and trial durations are frequently less than one year.

An example of the difficulty in obtaining consistent results can be found in assessing the impact of shade tolerance on response to some of the factors expected with climatic change. Shade tolerant species are typical of the later successional stages in an ecosystem, and are not considered to be opportunistic in nature (Bazzaz *et al.*, 1990). A three month study of four birch species showed this to be true in that the shade tolerant species were less responsive to CO_2 enrichment. However, in another study of seven different tree species (one-year-old seedlings treated for two months), it was the shade tolerant trees that expressed opportunistic behaviour by having the greatest increase in height growth (Bazzaz *et al.*, 1990; Rochefort and Bazzaz, 1992). These conflicting results are possibly the outcome of different experimental parameters, as the ecosystems they represent could be limited by different factors.

Environmental limitations affect the growth and distribution of species. The rates of biological processes are restricted in the boreal forest by temperature. With a predicted rise of 2 to 4 °C in mean annual temperature over the next 100 years, vegetation productivity and species distribution will be affected (Kauppi and Posh, 1988; Singh and Wheaton, 1991). The vegetation response is likely to be more affected by the rate of climate change than by its magnitude, as species have climate-driven controls, as well as limitations. Higher spring temperatures may cause premature completion of heat requirements which will increase the risk of frost damage by allowing buds to open earlier (Hanninen, 1991). Higher annual temperatures and tropospheric ozone concentrations will likely increase the rate of respiration, thus making growth more expensive for trees (Ryan, 1991).

Other environmental factors will also change. Precipitation is expected to change in amount and pattern, with seasonal differences being an important factor. Summer drought is likely to occur more frequently, as a result of the evaporative demand being greater than the water supply, causing a net reduction in growth. However, it is anticipated that productivity will increase significantly in regions that are not moisture limited (Miller *et al.*, 1987; Schwartz, 1991; Williams, 1985). Disturbances are likely to change in type and frequency, causing new stresses and selection pressures.

Some of the limitations on the boreal forest will not change initially, or even at all. Light intensity is important in determining the net primary productivity of trees in the far north, with a little variance caused by the filtering effect of stratospheric ozone (U.S. E.P.A., 1988). Sunlight should not be influenced by the predicted climatic changes, other than by change in cloud cover, which remains unpredicted by GCM's. Soil nutrients limit the boreal forest ecosystem, with the availability of nitrogen and phosphorus having a large affect on forest productivity (Roots, 1989). Atmospheric chemistry will change as pollutant concentrations rise (volatile substances under higher temperatures convert to gas more readily, and the source of pollutants will increase with the increased use of fossil fuel). The new concentrations will affect nutrient budgets due to increased solute deposition, and the response to increased CO_2 concentration will be conditional to the supply of water, nutrients and light (Higginbotham *et al.*, 1985).

Benefits of climatic change have been predicted, based on enhanced growth observations which occurred in some experiments (Brown and Higginbotham, 1986); however, the experimental conditions are unlikely to be found under climate change conditions. The allocation of biomass varies with environmental conditions; for instance, increased competition for water and nutrients may result in a proportionally higher root biomass than at present (Bazzaz, 1990; Brown and Higginbotham, 1986; Higginbotham *et al.*, 1985; Kramer and Sionit, 1987; Luxmoore *et al.*, 1986). Temperature and drought stress may be offset by increased water use efficiency, depending on the species (Kramer and Sionit, 1987; Miller *et al.*, 1987; and Wheaton *et al.*, 1987). The cost of synthesis and maintenance of leaf proteins is reduced under high CO_2 concentrations (Wullschleger and Norby, 1992), and there is a significant increase in N, Ca, Al, Fe, Zn, and Sr uptake and nutrient use efficiency (especially K, and P) (Luxmoore *et al.*, 1986). The longer, warmer growing seasons expected will allow a higher rate of production, and accelerate nutrient cycling (provided litter quality is not limiting); this may help sustain the increased production capacity (Wheaton *et al.*, 1988).

Enhanced CO_2 concentrations can create a fertilizer effect as photosynthesis can be limited by the local and atmospheric CO_2 concentrations (Kimball, 1983). Under enriched CO_2 conditions, increase in biomass productivity has been observed in height growth, leaf area production, and branching (Wheaton *et al.*, 1987). A decrease in respiration cost and increase in the rate of photosynthesis (caused by CO_2 enrichment) result in a net benefit to the plant. Lodgepole pine, birch, and many other coniferous and deciduous species have shown growth increases with an increase in CO_2 concentrations (Bazzaz *et al.*, 1990; Higginbotham *et al.*, 1985; Kramer and Sionit, 1987; Rochefort and Bazzaz, 1992; Solomon, 1988). However, this is thought to be of short duration, as other limiting factors come into play. Longer experiments have shown plants to acclimate to raised CO_2, with a reduction in productivity over time (Bazzaz, 1990; Higginbotham *et al.*, 1985; Wullschleger and Norby, 1992). Juvenile plants are more flexible in CO_2 uptake than mature plants, and since the majority of experiments have been done on young plants (and infrequently with trees), the results should be interpreted cautiously for forestry.

The impacts of varying CO_2 concentration has been the theme of many recent studies on plant development, growth, and yield. Concentrations have typically been held at one, two and three times the current atmospheric CO_2 level. Bazzaz and Williams (1991) measured CO_2 concentrations at different heights within a mixed forest to clarify the conditions *in situ* for seedling growth. Measurements were taken from early March to late November to include a buffer around the growing season. The results indicated strong seasonal and daily variation in CO_2 concentration. The average concentration in the forest during the growing season was higher than in the northern hemisphere bulk air. Variation of concentration with height was highly significant. CO_2 concentration was highest (at 1.5 times bulk air concentration) near the forest floor, and the lowest at 12 m, the greatest height at which measurements were taken. It appears that plants experience a change in atmospheric CO_2 concentrations within their present life cycle by growing through a vertical CO_2 concentration gradient. Exposure to the highest CO_2 level occurs when they are juveniles on the forest floor. This should be considered when experiments are initiated and interpreted, as predictions of mature tree species' behaviour based on such experiments will be used within simulation models for climate change.

Forest simulation models, used for predicting the forest response to climatic change, are created from quantifiable characteristics which represent only a few of the interrelated forest properties and processes (Solomon *et al.*, 1984). Yearly growth, death and recruitment of tree species within a forest are predicted using characteristic parameters of species (such as maximum age and size, shade tolerance, fecundity, soil moisture, and temperature requirements) (Solomon and West, 1985). A drawback to this approach is the need for a large database on each species' biology and natural history, which may not be available. The forest is reduced to a series of quantitative equations which attempt to mimic ecological patterns, processes, complex interactions, and individual species sensitivity across scales. Basic data and principles are used to project the forest's response to climate change.

Scaling has been recognized as a problem for these prediction models (O'Neill *et al.*, 1988; Turner *et al.*, 1989). The transfer of forest and climate information across scales is difficult as the systems represented may change in behaviour at a different scale. There is a good summary of the literature on the aggregation of ecosystems in King (1990). With the use of hierarchy theory for the aggregation of heterogeneous data, extrapolation between scales has become more common in forest modelling (Allen and Star, 1982; O'Neill, 1988a,b).

There are several hundred models of forest dynamics that simulate temporal response (Lenihan and Neilson, 1995; Shugart *et al.*, 1986). FORENA is an example of a model that operates at the scale of the individual stand (stand-level model). This model predicts a universal die back of current forests in response to climatic warming, and an invasion into the southern boreal forest by temperate deciduous trees (Graham *et al.*, 1990). Gap models are more frequently used than stand-level models because they can simulate increases in tree growth over time, and do not require large data sets. These models have been the most successful in simulating forest response to climate change (Shugart *et al.*, 1986).

Empirical models assume the present forest communities will be analogous to future communities, only found in different locations (Manning *et al.*, 1990). These models assume community dynamics can be imitated mathematically, and that the range of individual tree species is limited by climate alone. Correlation is used between data sets of biological and climatic factors from the present community and those generated for the future climate, with potential causes and effects substituted for those that are not known (Solomon and West, 1985). Simulation models are generally preferred over empirical models because the complex dynamic response patterns of the forest may be inadequately represented by empirical methods.

Forest-level response to climate change will vary greatly with the magnitude and duration of the change (Kauppi and Posh, 1985). A rapid warming may cause flooding, soil erosion, loss of soil fertility, and an increase in fire, insect, and disease outbreaks (Larsen, 1989). Establishing stands may not be able to reproduce before the climate becomes deleterious, which would cause a break in migration, and possibly bring about the loss of the population without intervention (Singh and Wheaton, 1991; Solomon, 1989; U.S., E.P.A., 1988; Wheaton *et al.*, 1987).

2.4 Summary

Global climatic changes have resulted in species distribution and composition changes over the past 600 million years. With the prediction of a rapid increase in global temperature and related changes to weather patterns over the next hundred years, further changes are expected in species distribution.

The rate and extent of climate change is predicted to vary over the planet's surface, with the Arctic being affected sooner and more intensely than the tropics. The northern forest regions have adapted to a low net energy input, and are therefore expected to be more sensitive than other systems to the changing climate.

The present composition of northern forests has resulted from climate change in the past. Information on species distribution and growth patterns over a range of climate conditions are available through Canada's national forest inventory[2] and from past climate records. The northern forests are therefore

[2]Maintained by the Canadian Forest Service.

an attractive subject for climate relationship studies, and possible projection through climate change scenarios. The heat-restricted, cool climate ecosystems may change in composition and growth patterns with the predicted rise in temperature and varied changes in precipitation. The change in local growing conditions may stress the existing vegetation, increase its susceptibility to pest outbreaks, and increase its fire event frequency.

Prediction of climate change affects on the boreal forest may be approached in a myriad of ways. Forest simulation models, for example, attempt to mimic the inter-related processes which determine ecosystem response to changes in the environment. The environmental changes used in these simulations may be the result of coarse resolution GCM's or linear climate record projections, typically with poor representation of specific geographical areas. Therefore, the present climate-to-species relationships should be the subject of concentrated study until finer resolution climate predictions are available for these relationships projections through climate change.

Chapter 3 Forest Inventory and Species-to-Climate Regression Relationships.

The objective of this chapter is to describe the procedure used to refine and transform the initial forest inventory information and to develop relationships between baseline climatic conditions (1951-1980), and species productivity and proportional occupancy on an inventory unit level. These relationships were used in the MBFP model described in Chapter 4. The word 'productivity' is used throughout this work to represent the selected tree species volume increment within inventory units based only on climate conditions.

3.1 Methods

3.1.1 Refining and Compiling the Initial Forest Inventory.

Provincial and territorial stand-level inventories were compiled for the Mackenzie Basin, from British Columbia, Alberta, Saskatchewan, Northwest Territories, and Yukon, covering 178 million hectares. Six[3] of the 12 species present were chosen for use in this study, based on their wide distribution and interest for future commercial use: black spruce, white spruce, lodgepole pine, Jack pine, paper birch and trembling aspen.

The Mackenzie Basin inventory database included provincial and territorial inventories taken over the past 20 to 30 years (depending on location). Data were obtained from the National Forest Database[4] for all provinces and territories except Alberta, which supplied a portion of its Phase III[5] data (1976 to

[3] Lodgepole and Jack pine were treated as one species in the analysis due to their ability to interbreed, and common characteristics. They will be referred to as "pine" from this point onwards, and the number of species will be considered to be five.

[4] Maintained by the Canadian Forest Service.

[5] Alberta Environment Protection, Forest Inventory.

1993) for the project[6]. Fourteen variables in the database were used to define stand records found within each of the inventory units (Table 1). No site classification variables nor measures of stand density were available. A fifteenth variable called "stand volume" was created by summing the merchantable volumes per ha of the five selected species,[7] (references made to the "stand" in this text refer to the grouping of these five selected species).

Inventory units were each geo-referenced with a unique set of latitude and longitude values at the unit centroid. Stand-level data (records of individual stands) within each inventory unit were not geo-referenced in the National Forest Database, but were associated with the geographic location of the inventory unit in which they were recorded. Inventory units varied in size and shape throughout the Mackenzie Basin, and contained multiple stand records. The stand-level data were aggregated within each inventory unit (described later). As part of the aggregation process, stand-types were defined from the stand records by age, main genus and forest type.

In the Mackenzie Basin inventory database, there were 975 possible stand-types. The area occupied by each stand record of a single stand-type within a unit was used for weighting when calculating the weighted mean inventory unit species volume per ha for that stand-type using SAS.[8] This reduced the number of records in the database so that each unit contained one record per stand-type with: (1) the total area occupied; (2) the mean weighted volumes per hectare for each species; (3) the proportion by volume of each species; and (4) a frequency count representing the number of stand records comprising that stand-type. This procedure is illustrated in Figure 1, where a hypothetical inventory

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[6] These data were organized and completed by Ross Benton, Forest Climatologist, Pacific Forestry Center, Canadian Forest Service, Victoria.

[7] All volumes recorded in the inventory database were merchantable. These have been referred to as volume in this text.

[8] The weighted mean unit values for stand-types were calculated by Ross Benton (Forest Climatologist, Pacific Forestry Center, Canadian Forest Service, Victoria).

Table 1. Description of the initial database variables.

Variables	Description	Values
Location		
1) Province	Province or Territory	AB Alberta BC British Columbia NT Northwest Territories SK Saskatchewan YT Yukon Territory
2) Unit	Unit Identification Label	10 Characters wide (numeric and character)
3) Latitude	Unit Centroid Position	to the sixth decimal original range 49.0433753 - 69.6677700 forest land with complete records range 49.0433753 - 62.0681110
4) Longitude	Unit Centroid Position	to the sixth decimal original range 105.6837540 - 141.0373380 forest land with complete records range 110.0769808 - 131.3977660
Area Covered		
5) Hectares	Hectares the stand covers within the unit	Integer
Forest Characteristics		
6) Main Genus	Predominant Species in the Stand	1 Spruce 2 Pine 3 Fir 4 Hemlock 5 Douglas fir 6 Larch 7 Cedar and other Conifers 8 Unspecified Conifers 9 Poplar 10 Birch 11 Maple 12 Other Broad-leaved species 13 Unspecified Broad-leaved species -8 Missing value -9 Non Applicable due to stocking level or landclass original range -9 - 13, forest land with complete records range 1 -10

Table 1 -- Continued

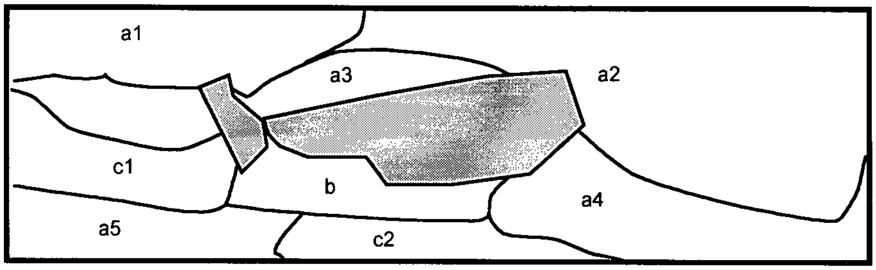
Variables	Description	Values
7) Forest Type	Stands Forest Type	1 Softwood 2 Mixedwood 3 Hardwood 8 Missing value 9 Non Applicable due to stocking level or landclass Original range 1 to 9, forest land with complete records range 1 to 3
8) Age Class	Age Class of Even-aged Stands in 20 Year Classes	0 0 years 1 1 to 20 years 3 21 to 40 years 5 41 to 60 years 7 61 to 80 years 9 81 to 100; or 81+ years 11 101 to 120; or 101+ years 13 121 to 140; or 121+ years 15 141 to 160; 141 to 250; or 141+ years 20 161+ or 251+ years -5 uneven-aged -8 missing values -9 not applicable Original range -9 to 20, forest land with complete records range 1 to 20
9) Maturity Class	Maturity Class of Even-aged Stands	1 Regeneration 2 Immature 3 Mature 4 Over mature 5 Uneven-Aged 8 Missing Value 9 Not Applicable Original range 1 to 9, forest land with complete records 1 to 4
10) Black Spruce	Species Merchantable Volume (m^3/ha)	
11) Other Spruce	Species Merchantable Volume (m^3/ha) (Volumes for White, Englemann, Norway, and Sitka Spruce, White Spruce only in the Mackenzie Basin)	
12) Pine	Species Merchantable Volume (m^3/ha) (Jack and lodgepole pine)	
13) Trembling Aspen	Species Merchantable Volume (m^3/ha)	
14) Paper Birch	Species Merchantable Volume (m^3/ha)	

unit's multiple records of stand-types a, b, and c are aggregated, with details of the calculations shown in the adjoining tables.

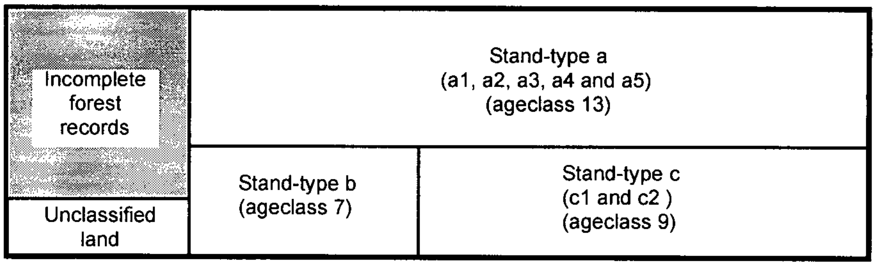
Calculating the species productivity measures (discussed below) required observations for 10 of the 15 stand-type variables. Records with incomplete observations for latitude, longitude, unit label, hectares, age class, or any of the five species, were removed from the database prior to this analysis using SAS version 6.07 on the University of British Columbia's mainframe computer system. Further removal of stand-type records were made for outliers based on validity thresholds for the area and stand volume variables. Stand-type records with stand volumes unrealistically high (indicating growth greater than 4 m^3/ha per year) were removed. Inventory unit records with areas smaller than 100 ha were removed for the regression procedures, as weighted regressions were not performed, and the high volume values possible in small stand-type area records may have introduced a bias. Large area stand records (greater than 10500 ha) were removed prior to regression procedures, as their validity was questionable.

As no site classification nor stand density measures were available, forest land productivity for the five species was based on age class and standing volume. The mean decadal increment (MDI) for each species was calculated for each stand-type within a unit by dividing the standing volume (m^3/ha) by its recorded age class, in decades. MDI served as a measure of the average periodic growth of each species within a stand-type. Overall weighted mean unit MDI values and weighted mean unit age values were needed from the stand-type records. These were obtained by using the area occupied by each stand-type within the unit as the weighting variable (Figure 2). Each species' proportion by volume was also calculated as an overall weighted mean value. This process brought the data resolution up to unit level, where each record represented a unique geographic area of forested land with complete records.

A)



B)



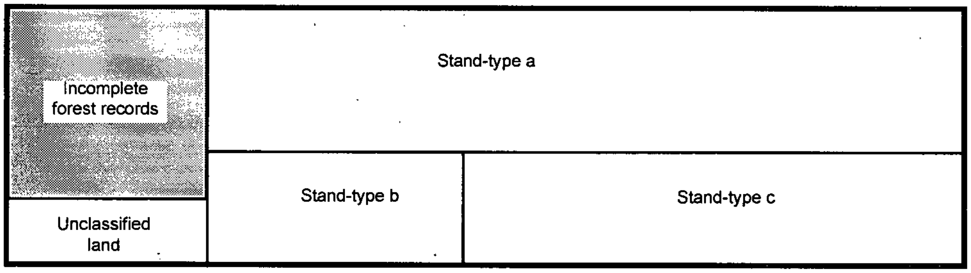
C)

Stand-type Multiple Records for unit BC 094C14E	Size (ha)	Black Spruce (m3/ha)	White Spruce (m3/ha)	Pine (m3/ha)	Trembling Aspen (m3/ha)	Paper Birch (m3/ha)
a1	79	0.00	21.60	79.70	0.00	0.00
a2	182	0.00	25.45	62.40	0.00	0.00
a3	142	0.00	26.55	92.20	0.00	0.00
a4	224	0.00	38.40	98.71	0.00	0.00
a5	64	0.00	34.80	88.60	0.00	0.00
b	256	0.00	19.90	0.00	24.10	0.00
c1	215	0.00	0.00	6.76	4.35	0.00
c2	167	0.00	0.00	5.25	3.55	0.00
Sum of Weighted Vol. (m3)	a:	0.00	20937.20	58527.70	0.00	0.00
	b:	0.00	5094.40	0.00	6169.60	0.00
	c:	0.00	0.00	2330.20	1527.75	0.00
Mean Weighted Vol. (m3/ha)	a:	0.00	30.30	84.70	0.00	0.00
	b:	0.00	19.90	0.00	24.10	0.00
	c:	0.00	0.00	6.10	4.00	0.00
Proportion by Vol.	a:	0.00	0.264	0.737	0.00	0.00
	b:	0.00	0.452	0.00	0.548	0.00
	c:	0.00	0.00	0.604	0.396	0.00

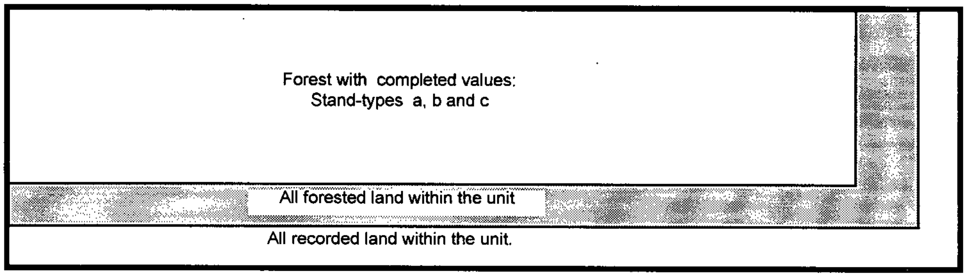
Figure 1. Summary of multiple stand-type records within an inventory unit.

A) Forest inventory unit with multiple records for forest stand-types a, b, and c.
B) Forest inventory unit after record summary, with mean weighted values for each stand-type.
C) Summary calculations for multiple records of stand-types.

A)



B)



C)

Stand-type for cell BC094C14E	Age Class	Size (ha)	Black Spruce		White Spruce		Pine		Trembling Aspen		Paper Birch	
			P	m3/ha	P	m3/ha	P	m3/ha	P	m3/ha	P	m3/ha
a	13	691	0.000	0.00	0.264	30.30	0.737	84.70	0.00	0.00	0.00	0.00
b	7	256	0.000	0.00	0.452	19.90	0.000	0.00	0.548	24.10	0.00	0.00
c	9	382	0.000	0.00	0.000	0.00	0.604	6.10	0.396	4.00	0.00	0.00
Sum of Weighted Values	14213		0.000	0.00	297.9	26031.7	739.7	60857.9	291.5	7697.6	0.00	0.00
Mean Weighted Unit Value (m3/ha)	10.70		0.000	0.00	0.224	19.59	0.557	45.79	0.219	5.79	0.00	0.00
Mean Decadal Increment (m3/ha/10years)				0.00		1.83		4.28		0.54		0.00

"P" refers to the Proportion within the cell

Figure 2. Summary of stand-types within an inventory unit.

A) Forest inventory unit with mean weighted volumes for each forest stand-type.
B) Forest inventory unit with stand-type summary values.
C) Summary calculations for stand-types.

The above summaries resulted in a data set that was manageable on a personal computer. Thus, further computations in the data set were done using SAS 6.04 (for DOS) on a 486DX/2 66MHz personal computer.

The loss of unit composition at the stand and stand-type levels was necessary in order to obtain a general unit growth value per species for later comparison with climate variables. A measure of MDI variation by species within units was derived, based on the weighted MDI observations for each species within each unit. This was calculated as:

$$\sigma^2 = \frac{\sum_{i}^{unit} (MDI^2 \times ha) - \frac{(\sum_{i}^{unit} (MDI \times ha))^2}{N}}{N}, \quad \text{where: } N = \sum_{i}^{unit} ha \quad \text{and} \quad MDI = \frac{\frac{m^3}{ha}}{ageclass}.$$

Since the data included all recorded stand-types in a unit, it was possible to calculate the 'true' variance for each species' MDI.

A measure of species productivity over the landscape was calculated at three levels of land area which were derived from the initial forest inventory. Total volume was summed for each species (species m^3/ha multiplied by the number of hectares occupied by each stand-type within an inventory unit) for the completed records within the unit, and then divided by the relevant unit land area. The land scales used within each unit were: (1) forested land with completed records; (2) all forested land; and (3) all recorded land (Figure 2). For representative forest-level analysis in this work, species productivity was based only on the complete forest record land base.

3.1.2 Species-to-Climate Regression Relationships.

Using weighted mean unit MDI for each species and proportional occupancy by each species within a unit, relationships with climate parameters were developed for the forested area with complete records throughout the basin.

The weighted mean unit MDIs for each species were grouped by the unit's age into one of six stages of species growth development. The boundaries between the age groups for each species were arbitrary, but were selected based on knowledge of the silvics of each species (Table 2). It is expected that the environmental conditions at the local scale will affect growth patterns, causing the time spent at each stage to vary. The age groups assigned are only rough estimates for the large area represented. The first three groups consisted of positive growth, with Age Group I comprising early, accelerating growth, Age Group II comprising the higher growth rates that occur as maturity is approached, and Age Group III comprising the lower growth rate of older stands. The latter three groups were assumed to have no growth or negative growth, with Age Group IV having no net increase, Age Group V comprising a 10% decrease in the standing volume over a ten year period, and Age Group VI resulting in the loss of all that species volume (through mortality) over a ten year period.

Table 2. Species age groups.

Species	Age Group					
	I	II	III	IV	V	VI
Black Spruce	0 to 50	51 to 120	121 to 200	201 to 230	231 to 250	> 250
White Spruce	0 to 50	51 to 120	121 to 200	201 to 230	231 to 250	> 250
Pine	0 to 40	41 to 80	81 to 120	121 to 150	------------	> 150
Trembling Aspen	0 to 30	31 to 70	71 to 80	-------------	81 to 120	> 120
Paper Birch	0 to 30	31 to 70	71 to 80	-------------	81 to 120	> 120
Stand	0 to 40	41 to 100	101 to 140	141 to 170	171 to 200	> 200

The climate variables used as potential independent variables for species occupancy and age group MDI relationships were: (1) mean monthly and annual temperatures, (2) total monthly, annual and summer (May to September) precipitation and mean annual precipitation; and (3) total monthly and annual potential evapotranspiration (ET_p), and mean annual potential evapotranspiration. The temperature and precipitation baseline values were generated for the Mackenzie Basin area (as a raster map surface) using 1951-1980 weather station records and SPANS linear interpolation; this was done by Smith and Cohen (1993).[9] The potential evapotranspiration values were generated by Ross Benton[10] using a modified Thornthwaite equation (which included day-length and temperature values, McKenny and Rosenberg, 1993) on the baseline temperature data supplied by Smith and Cohen (1993).

In order to compare the weighted mean unit MDI values across inventory units, required for building relationships with climate, the proportional occupancy of each species had to be normalized. This was done by calculating an adjusted species weighted mean unit MDI value which assumed full unit occupancy by each species (*i.e.*, each species' weighted mean unit MDI value was divided by its proportion occupancy to generate a MDI value for a "pure stand" of that species within the unit). Units were then represented through the combination of their proportional makeup by species and their adjusted species' weighted mean unit MDI values.

The range of productivity for each species within the inventoried area of the Mackenzie Basin was used as an indicator of specific growth responses to environmental conditions. This required the assumption that the values for the productivity of each species found in the inventory were

[9] For more detail on the adjustments made to the climate station data, and interpolation process used by Smith and Cohen see MBIS Interim Report #1, March 1993.

[10] Forest Climatologist, Pacific Forestry Center, Canadian Forest Service, Victoria.

representative of the species growth, and that the species were at equilibrium with the environment. Relationships were developed between species growth (Age Groups I, II, and III, separately) and the baseline climate conditions, by regressing the adjusted species' weighted mean unit MDI on the climate variables for each species first three age groups. Proportional occupancy of each species within the inventory unit was used as a measure of a species-specific establishment response to environmental conditions. Hence, relationships between proportional unit occupancy and climate conditions were also developed using multiple regression techniques.

Candidate independent variables for the regression equations were selected from the 42 possible climate variables for 23 prediction equations.[11] This was done by examining climate variable correlation and covariance matrices, and the partial coefficients of determination for each climate variable when predicting stand weighted mean unit MDI for Age Groups I, II, and III. A representative variable was chosen from within a group of highly correlated variables (as determined from correlation matrix) for use in the equations in order to reduce the impact of multicollinearity. This selection was based on the partial coefficients of determination generated for each of the highly correlated variables when predicting stand MDI (Age Groups I through III), and on previous predictive use of the variables in the literature. (See for examples: Booth, 1990; Booth and Jovanovic, 1988; Booth *et al.*, 1989; Cumming and Burton, 1995; Jozsa and Powell, 1987; Kauppi and Posch, 1985; Newnham, 1968; Sargent, 1988; Schönau and Schulze, 1984; Webb *et al.*, 1984).

The adjusted species weighted mean unit MDI and proportional occupancy for each species were regressed on the selected climate variables using a forward stepwise procedure with the significance

[11] Five species, each of which require three equations for productivity (Age Groups I, II, and III), and one equation for proportional occupancy. The total stand volume measure requires equations for the three age groups, which brings the total regression equations for development to 23.

level of entry set to 0.05 and the significance level to remain set to 0.049. If no climate variables were selected at this entry level, the level was lowered until at least one climate variable was selected.

3.2 Results

3.2.1 Refined Forest Inventory

The initial Mackenzie Basin forest inventory covered 84% of the Mackenzie Basin area with 653,464 stand records for 15,860 inventory units. Forested land covered 27% of the basin area, with 11,269 units recorded. After the removal of stand, stand-type and unit record outliers (Table 3), 18% of the Mackenzie Basin was found to have the values needed for this study. These records were found within Yukon Territory and the provinces of British Columbia and Alberta (Table 4). The lack of information on age class and geographic location for Saskatchewan and the Northwest Territories excluded these regions from further analysis.

The mean size of the units used in the regression analysis was 5015 ha with a standard deviation of 2962 ha (Table 4). Alberta contained 3808 useable inventory units with mean size of 4517 ha, and standard deviation of 2406 ha. British Columbia had 2158 useable inventory units with mean size of 6064 ha and standard deviation of 3530 ha. Yukon Territory had 452 inventory units with a mean size of 4207 ha and a standard deviation of 2890 ha. After aggregating the stand records to weighted mean unit stand-types, there were 146,224 stand-type records within the 6418 inventory units. The number of stand records per stand-type ranged from 1 to 198 with a mean of 4.48.

After further record aggregation, weighted mean unit values for age, proportion by volume, and MDI were generated. A summary of the MDI values calculated for the inventory units containing complete records are presented in Table 5, by species, for each of the inventory land scales. The difference in land area represented between the forested records and the complete records was minimal, as the

Table 3. Deficiencies and outliers defined for the initial database.

Description of outliers and deficiencies	Observations		Units		Number of Hectares		Comments
	Removed	Remaining	Removed	Unaffected	Removed	Remaining	
All Data (raw)	0	146224	0	16010	0	150090666	Initial Data received
Remove Obs. with ha=0.00	305	145919	289	15721	0	150090666	All records in AB.
Remove Obs. with ha='.'	149	146075	149	15861	0	150090666	All records in AB.
Remove Obs. if Stand ha>10500	570	145654	564	15446	10394471	139696195	All records in BC, SK NT
Remove Unit if total ha<100	-----	-----	270	15740	6005	150084661	No units this small in SK.
Remove Obs. if Vol.=0.00	25871	120353	13366	2644	101783818	48306848	
Remove Obs. if Vol.=Non-Applic.	2464	143760	2244	13766	14759758	135330908	All records are in B.C.
Remove Obs. if Vol.='.'	149	146075	149	15861	0	150090666	All records in AB.
Remove Obs. if Age Class is Missing or Non-applicable	19825	126399	12211	3799	116314185	33776481	
Remove Obs. if Lat or Long='.'	225	145999	54	15956	10639255	139451411	All records in SK
Remove Obs. if Stand-type Vol.growth $>4m^3$/ha/year	171	146053	150	15860	1622375	148468291	
Forested (Remove Obs. if no forest values present)	12490	133734	12254	3755	102029543	48061123	11269 units remain in the forested data set.
Obs. for Regression (Removal if Age Class, ha or total stand volume unwanted as described in text)	20256 (without unit removals)	125968	3624	12386	116404292	33686374	6418 units remain in the data set for growth analysis (in AB., B.C. and Y.T.)

Missing value in the data '.'

Table 4. Range of unit size for three land scales (Initial, Forested, and Growth Analysis).

	N (Population)	Mean Unit Size (ha)	Standard Deviation (ha)	Minimum Unit Size (ha)	Maximum Unit Size (ha)
1) All Initial Observations within Units					
Mackenzie Basin	15860	9463.47	28974.12	1.00	1335661.00
Alberta	4024	4565.51	2550.28	1.00	9400.00
British Columbia	2245	12588.36	5611.14	4.00	42672.00
Northwest Territories	7887	9876.24	2664.19	100.00	50000.00
Saskatchewan	54	197023.24	458281.84	823.00	1335661.00
Yukon Territory	1650	9045.48	2451.63	25.00	10045.00
2) Observations of Forested Land					
Mackenzie Basin	11269	4264.90	3258.14	1.00	66984.00
Alberta	4024	4565.51	2550.28	1.00	9400.00
British Columbia	2191	6162.08	3684.03	3.00	28057.00
Northwest Territories	4320	3121.92	2655.14	52.00	10000.00
Saskatchewan	54	10286.50	14276.15	31.00	66984.00
Yukon Territory	680	3156.28	2920.18	4.00	9592.00
3) Observations of complete Forest Records					
Mackenzie Basin	6418	5015.17	2962.14	100.00	26157.00
Alberta	3808	4516.61	2406.36	101.00	9400.00
British Columbia	2158	6064.02	3530.03	100.00	26157.00
Yukon Territory	452	4207.90	2889.63	113.00	9592.00

Table 5. Land productivity in the Mackenzie Basin over three land scales (N=6418 units). MDI are growth values shown in units of $m^3/ha/10$ years. The summed weighted MDI values are divided for each unit by the area of complete records, the area of forested land and the area of the entire inventoried unit. Weighted mean unit is WMU, all land is Z and forested land is F.

	Mean	Standard Deviation	Minimum	Maximum
1) Area of Units with Records in the Inventory (ha)	7681.22	5269.35	100.00	42338.00
ZWMU Black Spruce MDI	0.59	0.74	0.00	5.55
ZWMU White Spruce MDI	2.60	1.66	0.00	18.99
ZWMU Pine MDI	2.25	2.27	0.00	18.50
ZWMU Trembling Aspen MDI	2.25	2.15	0.00	15.92
ZWMU Paper Birch MDI	0.15	0.24	0.00	3.09
ZWMU Stand MDI	7.84	3.99	0.00	35.56
2) Area of Units with Forested Records (ha)	5158.18	3041.21	100.00	28057.00
FWMU Black Spruce MDI	0.82	1.18	0.00	9.54
FWMU White Spruce MDI	3.59	2.39	0.00	21.02
FWMU Pine MDI	2.84	2.79	0.00	23.48
FWMU Trembling Aspen MDI	2.78	2.82	0.00	35.81
FWMU Paper Birch MDI	0.19	0.38	0.00	8.01
FWMU Stand MDI	10.23	4.49	0.00	36.52
3) Area of Units with Complete Records (ha)	5015.17	2962.14	100.00	26157.00
WMU Black Spruce MDI	0.85	1.19	0.00	9.53
WMU White Spruce MDI	3.71	2.43	0.00	21.02
WMU Pine MDI	2.91	2.84	0.00	23.48
WMU Trembling Aspen MDI	2.90	2.87	0.00	36.02
WMU Paper Birch MDI	0.20	0.39	0.00	8.44
WMU Stand MDI	10.57	4.45	0.18	36.73

majority of incomplete forest records were within units with no complete records, and were therefore not included in the data set for regression analysis. As much of the inventoried land held no forest values, the difference between inventoried records and complete records in land area representation was greater. The weighted mean unit MDI values for complete records were used in the regression analysis after adjustment for proportional occupancy by each species. The MDI values varied by province and territory, both before and after proportional adjustment. The highest adjusted weighted mean unit MDI values for all the species occurred in Yukon, which had the fewest unit records (Table 6). The weighted mean unit age class values also varied, with the lowest values occurring in Alberta.

The weighted mean proportions per unit used for each species in the regression analysis are presented by region in Table 7. Yukon had the highest proportions for both black spruce (0.243) and lodgepole pine (0.341). British Columbia had the highest proportion for white spruce (0.443). The highest proportions of trembling aspen and paper birch were in Alberta (0.300 and 0.023 respectively).

3.2.2 Species-to-Climate Regression Relationships

The selected subset of 17 climate variables (potential independent variables for the regression equations), which contained 6 temperature, 6 precipitation, and 5 ETp measures, were accepted in different combinations for each of the final regression equations. The results of the multiple linear stepwise regression analyses completed for the proportional occupancy, and for the adjusted weighted mean unit MDI (by age group), for each species are given in Table 8. The R^2 values ranged from 0.098 (for Age Group I, white spruce, which had 173 observations) to 0.469 (for stand Age Group I, which had 68 observations). It was apparent that some of the regression relationships had poor predictive powers. This was especially evident for the deciduous species, and all species in Age Group I. However, all but three of the equations were highly significant (p values of less then 0.0001). (Paper birch and trembling aspen, both with 16 observations, and white spruce with 68

Table 6. Complete unit records from the Mackenzie Basin database as used in growth analysis. (MDI are growth values shown in units of m^3/ha/10years.)

	Mean		Standard Deviation		Minimum		Maximum		Adj N
	Norm.	Adj.	Norm.	Adj.	Norm.	Adj.	Norm.	Adj.	
Mackenzie Basin (N=6418)									
Unit Size in ha	5015.17		2962.14		100.00		26157.00		
Age class	9.146		2.707		1.000		20.000		
Maturity Class	2.686		0.397		1.000		4.000		
Black Spruce MDI	0.855	9.390	1.192	4.153	0.000	0.060	9.536	35.560	5140
White Spruce MDI	3.711	10.713	2.431	4.745	0.000	0.184	21.024	36.015	6393
Pine MDI	2.908	11.057	2.842	5.297	0.000	0.254	23.479	40.522	6211
Trembling Aspen MDI	2.899	11.215	2.869	4.863	0.000	0.100	36.015	37.182	6135
Paper Birch MDI	0.199	10.062	0.387	4.605	0.000	0.060	8.440	40.235	5153
Stand MDI	10.572	10.572	4.446	4.446	0.184	0.184	36.735	36.735	6418
Alberta (3808=N for all observations but the Adjusted Weighted Mean Unit Values)									
Unit Size in ha	4516.61		2406.36		101.00		9400.00		
Age class	8.206		2.717		1.000		20.000		
Maturity Class	2.717		0.444		1.000		4.000		
Black Spruce MDI	0.680	8.057	0.562	2.904	0.000	0.303	4.61	35.56	3807
White Spruce MDI	2.848	8.868	1.322	2.713	0.000	0.810	15.69	35.56	3806
Pine MDI	2.260	8.803	1.840	3.028	0.000	0.385	18.50	35.56	3807
Trembling Aspen MDI	2.962	9.504	2.003	2.809	0.000	0.752	14.92	35.560	3806
Paper Birch MDI	0.196	8.558	0.214	2.904	0.000	0.141	2.86	25.778	3785
Stand MDI	8.946	8.946	2.752	2.752	1.207	1.207	35.56	35.560	3808

Table 6 -- Continued

	Mean		Standard Deviation		Minimum		Maximum		Adj N
	Norm.	Adj.	Norm.	Adj.	Norm.	Adj.	Norm.	Adj.	
British Columbia (2158=N for all observations but the Adjusted Weighted Mean Unit Values)									
Unit Size in ha	6064.02		3530.03		100.00		26157.00		
Age class	10.574		2.914		3.056		20.000		
Maturity Class	2.589		0.298		1.554		3.189		
Black Spruce MDI	0.568	12.058	1.266	5.149	0.000	0.060	9.536	32.092	881
White Spruce MDI	5.023	13.153	3.180	6.117	0.000	0.184	21.024	36.015	2135
Pine MDI	3.456	14.299	3.515	6.541	0.000	0.254	23.479	40.522	1952
Trembling Aspen MDI	3.125	13.588	4.049	6.495	0.000	0.100	36.015	37.182	1877
Paper Birch MDI	0.237	13.245	0.597	6.382	0.000	0.060	8.440	40.235	928
Stand MDI	12.409	12.409	5.517	5.517	0.000	0.184	36.735	36.735	2158
Yukon Territory (452 =N for all observations but the Adjusted Weighted Mean Unit Values)									
Unit Size in ha	4207.90		2889.63		113.00		9592.00		
Age class	10.250		1.455		3.116		15.349		
Maturity Class	2.887		0.261		2.019		4.000		
Black Spruce MDI	3.699	15.411	1.062	2.900	0.017	9.651	7.968	26.281	452
White Spruce MDI	4.714	14.714	2.337	2.657	0.015	9.929	18.993	25.561	452
Pine MDI	5.752	16.050	3.766	3.251	0.073	8.295	17.099	32.759	452
Trembling Aspen MDI	1.299	15.769	1.424	3.265	0.000	8.144	10.333	26.310	452
Paper Birch MDI	0.037	16.289	0.025	3.228	0.000	9.913	0.184	25.091	440
Stand MDI	15.500	15.500	2.993	2.993	8.349	8.349	26.201	26.20	452

Table 7. Species weighted mean unit proportion for complete unit records from the Mackenzie Basin Database as used in species establishment analysis.

Weighted Mean Unit Proportion (WMUP).

	Mean	Standard Deviation.	Minimum	Maximum
Mackenzie Basin (N=6418)				
WMUP Black Spruce	0.0902	0.1036	0.000	0.8645
WMUP White Spruce	0.3666	0.2037	0.000	1.000
WMUP Lodgepole Pine	0.2632	0.2119	0.000	1.000
WMUP Trembling Aspen	0.2595	0.2049	0.000	1.000
WMUP Paper Birch	0.0203	0.0336	0.000	0.6955
Alberta (N=3808)				
WMUP Black Spruce	0.0942	0.0809	0.000	0.5406
WMUP White Spruce	0.3269	0.1382	0.000	0.8397
WMUP Lodgepole Pine	0.2559	0.2000	0.000	0.9898
WMUP Trembling Aspen	0.2998	0.1656	0.000	0.8909
WMUP Paper Birch	0.0231	0.0224	0.000	0.2469
British Columbia (N=2158)				
WMUP Black Spruce	0.0512	0.1145	0.000	0.8645
WMUP White Spruce	0.4432	0.2725	0.000	1.000
WMUP Lodgepole Pine	0.2598	0.2316	0.000	1.000
WMUP Trembling Aspen	0.2263	0.2540	0.000	1.000
WMUP Paper Birch	0.0194	0.0488	0.000	0.6955
Yukon (N=452)				
WMUP Black Spruce	0.2427	0.0643	0.0015	0.4692
WMUP White Spruce	0.3362	0.1781	0.0009	0.7902
WMUP Lodgepole Pine	0.3410	0.1953	0.0044	0.9373
WMUP Trembling Aspen	0.0780	0.0768	0.000	0.6621
WMUP Paper Birch	0.0022	0.0013	0.000	0.0092

Table 8a. The climate variables selected for each productivity (•) and proportion (◦) regression. (Age Groups noted by I, II, and III, and P for proportion.)

Potential Variables	Stand			Black Spruce				White Spruce				Pine				Trembling Aspen				Paper Birch			
Age Group (Species/Stand Specific)	I	II	III	I	II	III	P	I	II	III	P	I	II	III	P	I	II	III	P	I	II	III	P
JAN1980T (Jan. 1951-80 Temp.)	•	•				•	◦	•	•	•	◦	•	•	•	◦		•		◦			•	
MAY1980T (May 1951-80 Temp.)		•	•				◦		•		◦			•			•					•	
JUN1980T (June 1951-80 Temp.)						•	◦		•				•	•	◦		•		◦		•		
AUG1980T (Aug. 1951-80 Temp.)				•		•	◦		•		◦				◦		•	•					
SEP1980T (Sept. 1951-80 Temp.)		•	•			•	◦		•		◦		•	•	◦		•	•			•		
OCT1980T (Oct. 1951-80 Temp.)		•	•				◦		•	•	◦			•	◦			•	◦		•	•	◦
APR1980P (Apr. 1951-80 Precip.)		•		•		•	◦	•	•				•		◦			•			•	•	
JUN1980P (June 1951-80 Precip.)		•	•				◦				◦			•	◦				◦	•	•	•	
SEP1980P (Sept. 951-80 Precip.)		•	•		•		◦	•	•	•	◦		•	•	◦		•		◦			•	◦
OCT1980P (Oct. 1951-80 Precip.)		•	•				◦		•	•	◦			•	◦	•	•		◦				◦
TOTPSUMR (Tot. Summer Prec)			•	•		•					◦	•		•	◦								◦
MANNPRCP (Mean Ann.Precip.)	•	•	•		•			•	•	•			•	•	◦			•	◦		•	•	◦
APR1980E (Apr. 1951-80 ETp.)		•	•		•	•	◦			•			•	•				•	◦			•	
MAY1980E (May 1951-80 ETp.)	•			•			◦		•	•			•		◦			•	◦	•			◦
AUG1980E (Aug. 1951-80 ETp.)						•	◦		•		◦				◦		•		◦				
OCT1980E (Oct. 1951-80 ETp.)		•			•	•	◦		•	•	◦		•	•			•		◦		•	•	◦
ANN1980E (Ann. 1951-80 ETp.)		•					◦		•														

Table 8b. Statistics for the productivity and proportion regression equations. (Age Groups noted by I, II, and III, and P for Proportion.)

Age Group		Number of Observations	Number of Variables Included	R2	(MSEe)½
Stand	I	68	3	0.469	5.301
	II	4130	12	0.455	3.125
	III	1852	9	0.442	3.511
Black Spruce	I	151	3	0.149	4.888
	II	4588	4	0.438	3.080
	III	401	9	0.375	3.356
	P	6418	15	0.318	0.086
White Spruce	I	173	4	0.098	5.834
	II	5304	14	0.459	3.469
	III	916	8	0.304	3.341
	P	6418	11	0.247	0.176
Pine	I	68	2	0.308	5.146
	II	2238	9	0.335	3.857
	III	3073	12	0.476	4.041
	P	6418	13	0.297	0.178
Trembling Aspen	I	16	1	0.276	4.537
	II	1440	9	0.130	3.432
	III	897	7	0.308	3.096
	P	6418	11	0.408	0.1577
Paper Birch	I	16	2	0.432	3.673
	II	1299	7	0.110	3.532
	III	813	9	0.220	3.458
	P	6418	7	0.142	0.031

All but three of the equations had p values of less then 0.0001 (the exceptions were in Age Group I for white spruce, paper birch and trembling aspen).

observations, all in Age Group I were the exceptions.) Two of the equations (paper birch, and white spruce, both Age Group I) required reductions in the level of significance for entry before any climate variables were selected. The coefficients for all these equations are given in Appendix 2.

3.3 Discussion: Forest Inventory, and Regression Relationships.

The initial forest inventory database for the Mackenzie Basin contained individual stand records within inventory units with a unique geographic location. Individual stands of poor quality, noncommercial species, or young ages may not have been recorded in the initial inventory, which then generates a biased representation of the measured forested land. Of the recorded inventory, many of the records were found to be incomplete, and were removed. Lack of inventory values may have been due to incompatible land class (such as rock, ice or open water), a recent fire or logging operation, or a mistake in the recording process.

Provincial and territorial forest inventories vary in requirements and methods of data collection. Northwest Territories' observations were predominantly made using remote sensing, which only provided forest type, location and area. Alberta and British Columbia differ in the application of yield models, which assign volume values, causing a political disparity of volume records between similar forests.[12]

The aggregation of forest stand records within an inventory unit (executed in this chapter), may have improved representation of the actual forest by balancing the over- and under- estimations made within the national inventory. To avoid an over-estimation bias from the forested land reported here, extrapolations made for larger land areas must consider the limitations associated with generating the

[12]An example of this difference in volume between provinces can be seen in Figure 4, Chapter 4.

inventory subset analyzed.

The 1951-1980 climate variables used for the Mackenzie Basin were generated from 121 climate stations with 25 or more years of records in that period. Of these stations, only 5 were located above 1000 m elevation. Attempts were made to account for the Mackenzie Mountains elevation effects; however, elevation and aspect were poorly represented by the temperature and precipitation baseline climate database for the Mackenzie Basin in general. This affects the site-specific predictive powers of the regression equations, as some stands of low productivity and high elevation were falsely associated with lower elevation climate conditions..

The regression analysis performed on species productivity was divided by age groups assigned to the life cycle stages of tree growth. The climatic variables used in the regressions were a subset of the temperature, precipitation, and ETp measures available. It may be possible to improve the productivity and proportion of occupancy regression relationships by adjusting the climate variable subset for each species and age group, as the subset used was selected, in part, by the partial coefficients of determination for each climate variable when predicting stand MDI for Age Groups I, II, and III.

Establishment and possible succession relationships may be improved by stratifying the database by age. Stands less than 80 years could be used for building initial establishment relationships, as the five species modelled are present in Age Groups I through III, without species exclusion through over maturity and death. A possible measure of succession would be achievable by comparing species proportions from the initial establishment proportions, the 81 to 200 year old stand records, and the records greater than 200 years old.

The poor predictive power of the regression relationships for deciduous species, and all species in Age Group I, are understandable given that there were relatively few observations for each of the first age groups, and that records for deciduous trees were not emphasized in past inventories. To improve databases for research purposes, the scope of traditional commercial inventories should be increased. Poor productive lands, non-commercial species and locations for each observation within an inventory unit would begin the list of additional records to be taken in a research-oriented inventory. This would improve the range of the data, and thereby improve the extent to which the predictions could be extrapolated in the future.

Variability in forest growth is associated with many different environmental variables, of which monthly climate measures of temperature, precipitation, and ETp are a few. The lack of site information on condition and stand density in the inventory reduced the possible predictive powers of the relationships developed for species productivity and proportional occupancy. However, the predictive relationships (highly significant, though with low coefficients of determination; see Table 8) were designed to be used with climate change scenarios. Predictions of climate-induced change in forest site conditions (including soil water balance and nutrient mineralization rates) are not readily available, and therefore their inclusion in empirical relationships that are to be projected through climate change scenarios would be inappropriate.

Insect attacks which reduce species productivity presently vary with climate conditions and stand composition. The inventory did not record attacks on forest stands, and therefore the productivity measures generated for each species in an inventory unit included insect-generated reductions in productivity. If the level of growth reduction caused by insects at the inventory unit scale is assumed to be directly related to climate conditions only, then the productivity-to-climate relationships will include insect-caused reduction in growth as they are applied through climate change scenarios. This assumption was made, eliminating the need for a separate measure of the impact of insects on species growth.

The direct association of species growth to climate over a large range of climate conditions and geographic areas assumes a continuous response potential for species. Growth response to climate conditions vary with provenance. A change in the climate conditions would likely alter the resident provenance's growth (Eriksson, 1982; Erriksson *et al.*, 1993). The species productivity measures generated in this chapter were done with provenances assumed to be in their preferred climate. Under climate change, provenances will be growing in new conditions. This assumption may cause over- or under-estimation of productivity across the provenances, and should therefore be remembered as a source of error when analyzing the MBFP model results.

The unit composition, lost in the process of obtaining mean unit values, may be represented by the MDI variance within units that was calculated for each species. These variances could be used in several ways to accommodate small-scale studies requiring the projection of MDI values through climate change processes. One use would be to generate a normal distribution of MDI values from the mean unit value for each species using the species' MDI variance within the unit. If this was done for generated future mean unit MDI values from the MBFP model, the assumptions of MDI normality and of constant MDI variance within units through climate change would have to be made. An argument for the assumption of constant MDI variance within units over time is that the unit-specific variation in physical and environmental conditions (such as parent material, elevation, slope, aspect and drainage) that affect species growth changes over a different time scale than climate. Another possible use for small-scale studies using MDI variance within units would be to build relationships with climatic variables (as has been done for species productivity and proportion values). The assumption of species MDI variance within units being related to climate would have to be made.

Then, generated future values of variance within units from the MBFP model could be used to create normal distributions of MDI for each species. For the scale used in this work, mean unit values were sufficient, as that was the lowest resolution at which climate and inventory records could be related and modelled.

3.4 Summary: Forest Inventory and Species-to-Climate Regression Relationships.

From the initial forest inventory for the Mackenzie Basin, 42% of the units recorded met the inventory requirements for this study. These units were found within Yukon Territory and the provinces of British Columbia and Alberta. They were studied for the range of climate conditions and the associated growth of the five predominant boreal tree species.

Estimates of mean decadal increment, age, and proportional occupancy were derived from the inventory for each of the five species. Paper birch occupied the smallest amount (2% by area) of the Mackenzie Basin units, closely followed by black spruce (9% by area). White spruce was the most prevalent of the five species, representing 37% of the Mackenzie Basin inventory unit area. The adjusted weighted mean unit MDI values in the Mackenzie Basin were highest for trembling aspen (11.2 m^3/ha/10years); however, all species were very similar, with means ranging from 9.3 to 11.2 m^3/ha/10years.

The growth and proportional occupancy values were then regressed with a selected subset of 17 climate variables to generate predictive relationships of climate-to-species productivity, and climate-to-proportional site occupancy. The relationships produced varied in predictive power; between 1 and 15 climate variables were used to describe the growth values. All but three of the relationships were highly significant. The relationships were developed for use in a forest model that would be run through climate change scenarios, as described in Chapter 4.

Chapter 4 Mackenzie Basin Forest Productivity Model

This chapter describes the MBFP model, and its component modules written for application to the refined forested area (as defined in Chapter 3). The model uses species-to-climate productivity and proportional occupancy relationships (as developed in Chapter 3). The MBFP model was built to analyse the effects of climate change scenarios, with sensitivity tests outlined for the climate-driven fire and growth modules.

4.1 Modelling Approach and Methods

The simplistic forest dynamics model, created for investigation of the effect of climate changes on the forest, was supported by the geographic information system (GIS) called GRASS (Geographical Resources Analysis Support System). This UNIX-based GIS worked well for the modeling component of the project. It supports shell script modeling, and performs arithmetic calculations on raster map-layers.[13] The use of GRASS helped co-ordinate data transfer within the MBIS research project. It was able to run on a personal computer using the Linux operating system (with GRASS to Linux binaries).[14]

The aggregated forest inventory unit values described in Chapter 3 were transferred from SAS to GRASS to create raster map-layers for use in the MBFP model. The variable size of the forest inventory units was accommodated by using a raster scale finer than the smallest inventory unit. The

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[13] Raster map-layers contain geographic information assigned to the centroid of regularly distributed cells over the map surface. The individual cell is called a pixel. Pixel values can be processed using arithmetic calculations in GRASS, with the current active resolution using data values from the closest pixel centroid. More information on GIS data storage can be found in any GIS textbook.

[14] Both Linux and GRASS are available as public domain software. Linux kernel version 1.1, Slackware 2.0, Infomagic, Rocky Hill, NJ. GRASS 4.1, United States Army Corps of Engineers, Construction Engineering Research Laboratories, Champaign, Illinois.

numerous raster pixels representing each inventory unit maintained the inventory unit's attributes throughout the MBFP model analysis. Data export from GRASS was achieved for each inventory unit using a single representative raster pixel.

The inventory units used in the regression analysis described in Chapter 3, plus inventory units with less than 100 ha of forested area, were used in the MBFP model as the complete landbase. The geographic distribution of these 6683 inventory units is shown in Figure 3.

Using GRASS, 13 raster map-layers were generated from the inventory unit attribute data in SAS. The maps contain: standing volume and proportional occupancy for each of the five species, unit mean weighted age, the forested area within the inventory unit, and a unique forest inventory unit label. The GISS GCM was selected for predicting changes to mean monthly temperature and precipitation in ten-year time steps up to the year 2050 AD (under a $2XCO_2$ concentration by 2030 AD scenario). This GCM was run at a 8°x10° resolution, and has been interpolated down to GRASS raster map surfaces with a spatial resolution varying from 2½ to 5 minutes (approximately 4.6 to 9.3 km).[15] Seasonal fire weather index (FWI) values, which indicate fire hazard based on temperature and precipitation, were also generated as GRASS raster maps from SAS data.[16] These maps, along with the calculated raster maps of total summer (May to September), annual, and mean annual precipitation, and monthly and annual ETp, were available for use in the MBFP model.

[15] The interpolation was done by Ross Benton (Forest Climatologist, Pacific Forestry Center, Canadian Forest Service, Victoria). No allowances were made in this interpolation for the influences of topography or large bodies of water.

[16] Seasonal FWI was generated from the mean of June, July and August FWI monthly values. The monthly values were calculated by Lisa Kadonaga, (graduate student, University of Victoria, Victoria) for 16 climate stations in the Mackenzie Basin. The method developed to generate monthly FWI measures was then used to create a series of monthly FWI surfaces for the Mackenzie Basin by Ross Benton (Forest Climatologist, Pacific Forestry Center, Canadian Forest Service, Victoria), which in turn were used in the calculations of seasonal FWI.

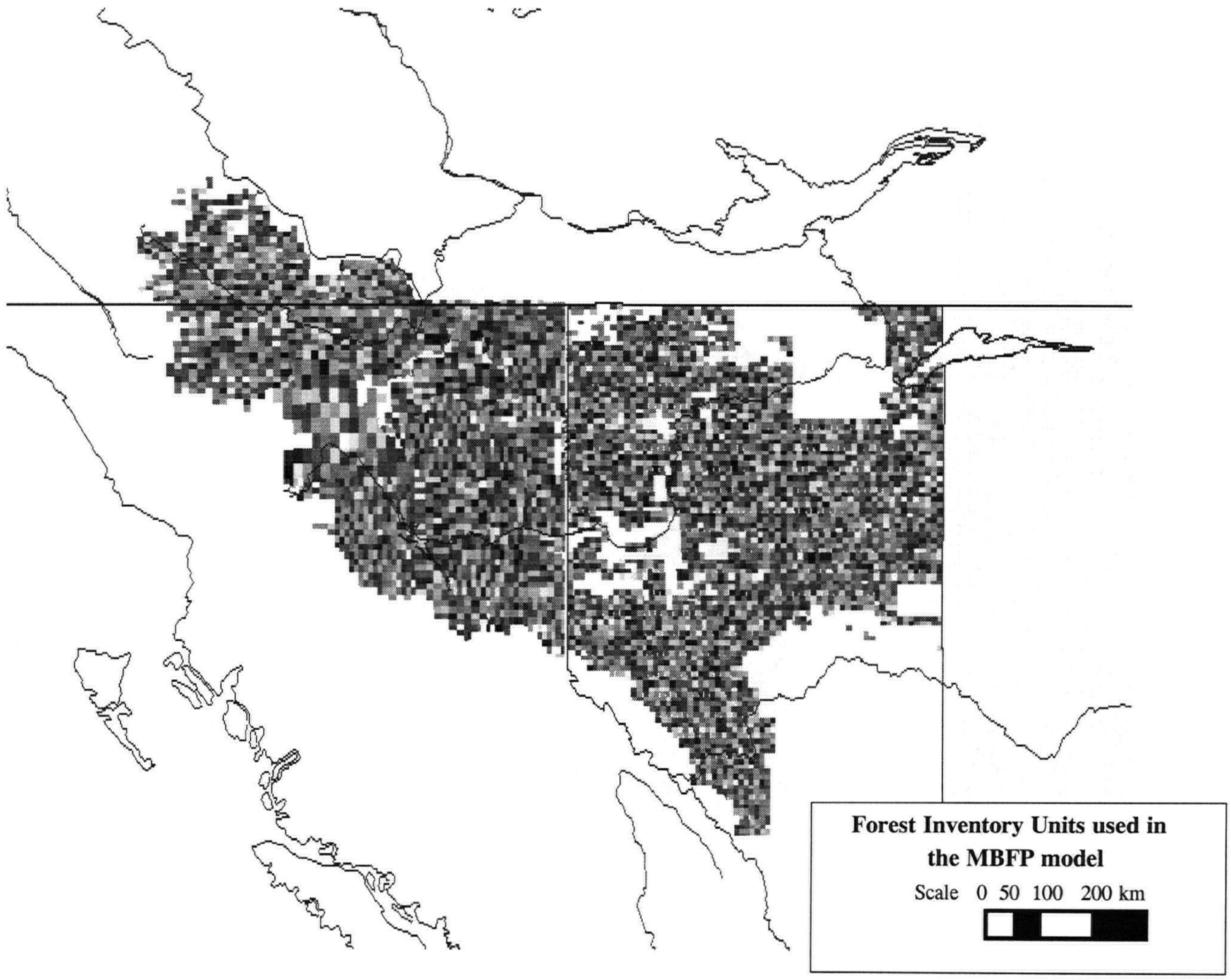


Figure 3. The forest inventory units used in the MBFP model.

A sample of the raster map-layers generated in GRASS are shown in Figures 4, 5, 6 and 7. Caution should be used when interpreting these images from the forest inventory, as they only represent the forested areas that met all the data requirements discussed in Chapter 3 (section 3.1.1). The 1980 standing volume (in m^3/ha) for the five species studied is represented for each unit in Figure 4, with the number of forested ha represented for each unit in Figure 5. Units which have high forest volume per hectare in Figure 4 may only have a small forested area within them. The overall forest productivity of an inventory unit depends on the age of the unit (Figure 6), the standing volume per hectare (Figure 4) and area of forested land recorded within the unit (Figure 5). The raster map-layer of the GISS 1980 seasonal FWI conditions is shown in Figure 7, with boundaries for three classes of seasonal FWI. All the climate map-layers used have a coarser resolution than the forest inventory, and provide complete coverage of the Mackenzie Basin area.

The approach used for the MBFP model employed the simplistic connection of the major forest dynamic processes presented in Figure 8. The processes of fire disturbance, species stress-induced mortality, species establishment, and growth, were arranged to run in ten-year time steps from 1980 to 2050 using the GCM scenario climate conditions. Within each ten-year time step, the species age groups used in assigning volume increment or reduction (Table 2), were reassessed with the new age value for each unit. The MBFP model completes a single run after all seven time steps have been executed. Standing volume for each species, unit age, and proportional occupancy by species can change for each inventory unit over the time steps of a single model run.

The sub-shell modules (described in detail later) created within the MBFP model super-shell represented: fire events, species death due to poor climate conditions, proportional establishment of the five species after unit disturbance, and individual species growth. (The code for each of

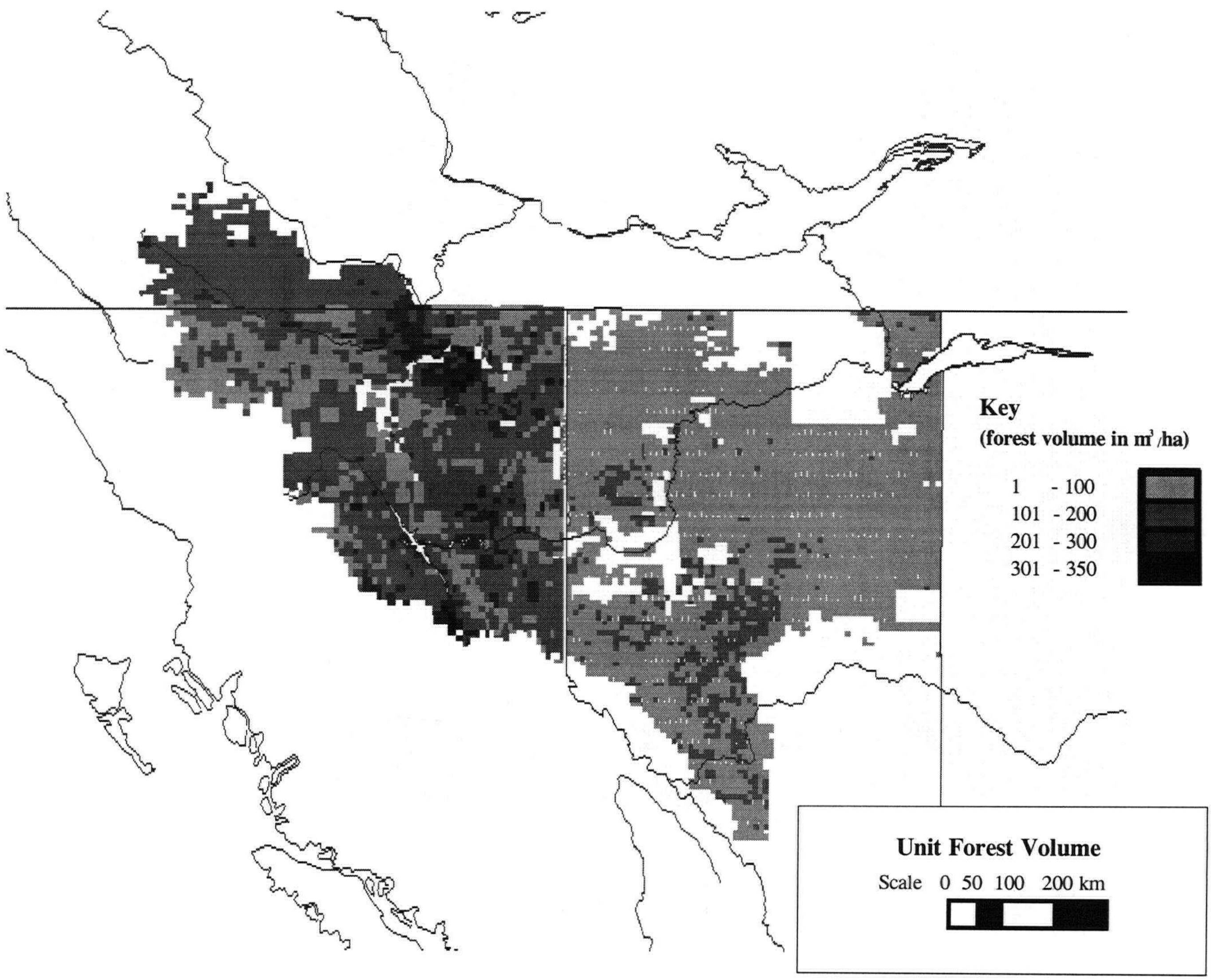


Figure 4. The standing volume of the five species summed within each unit, measured in m^3/ha

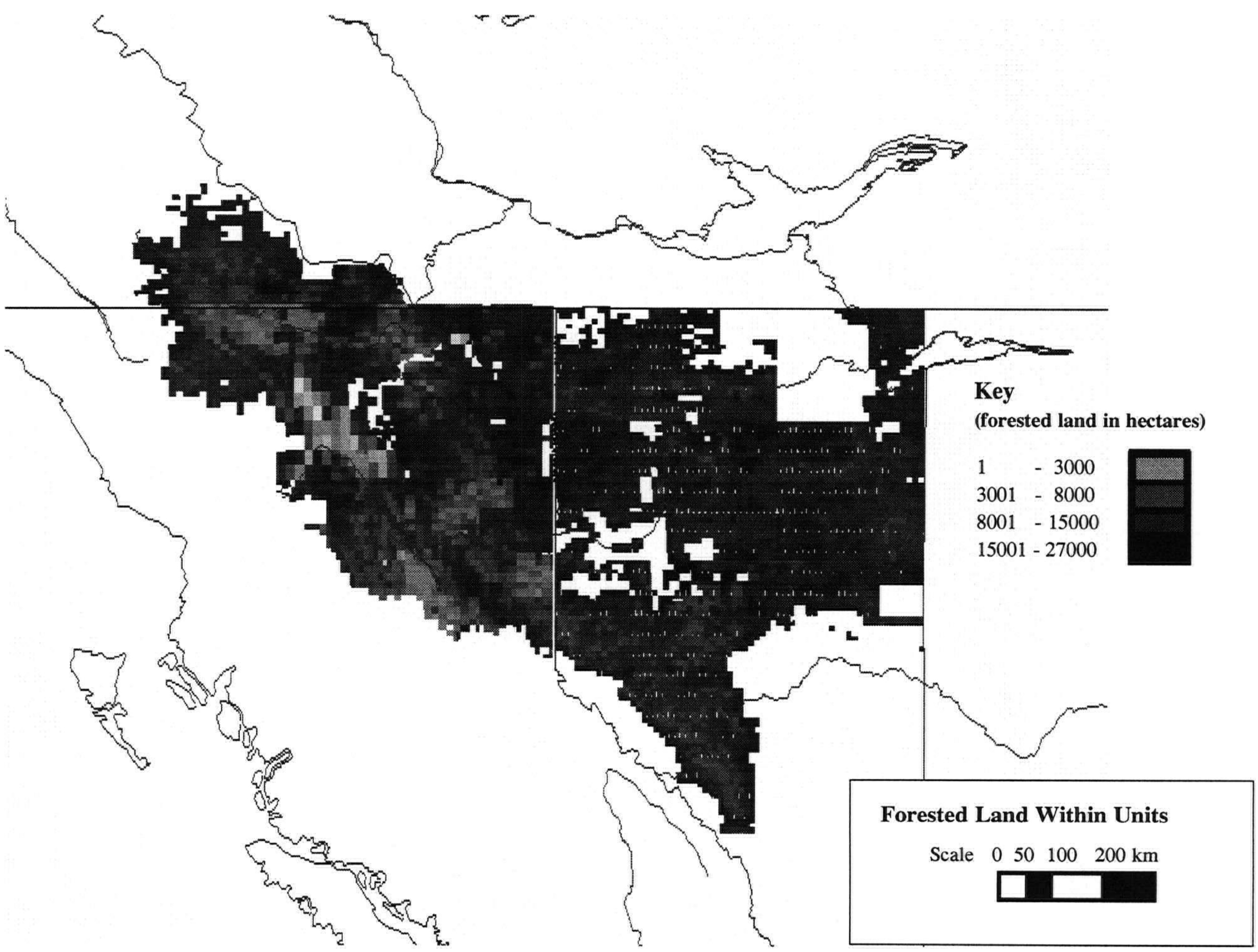


Figure 5. Number of forested hectares within inventory units for use in the MBFP model.

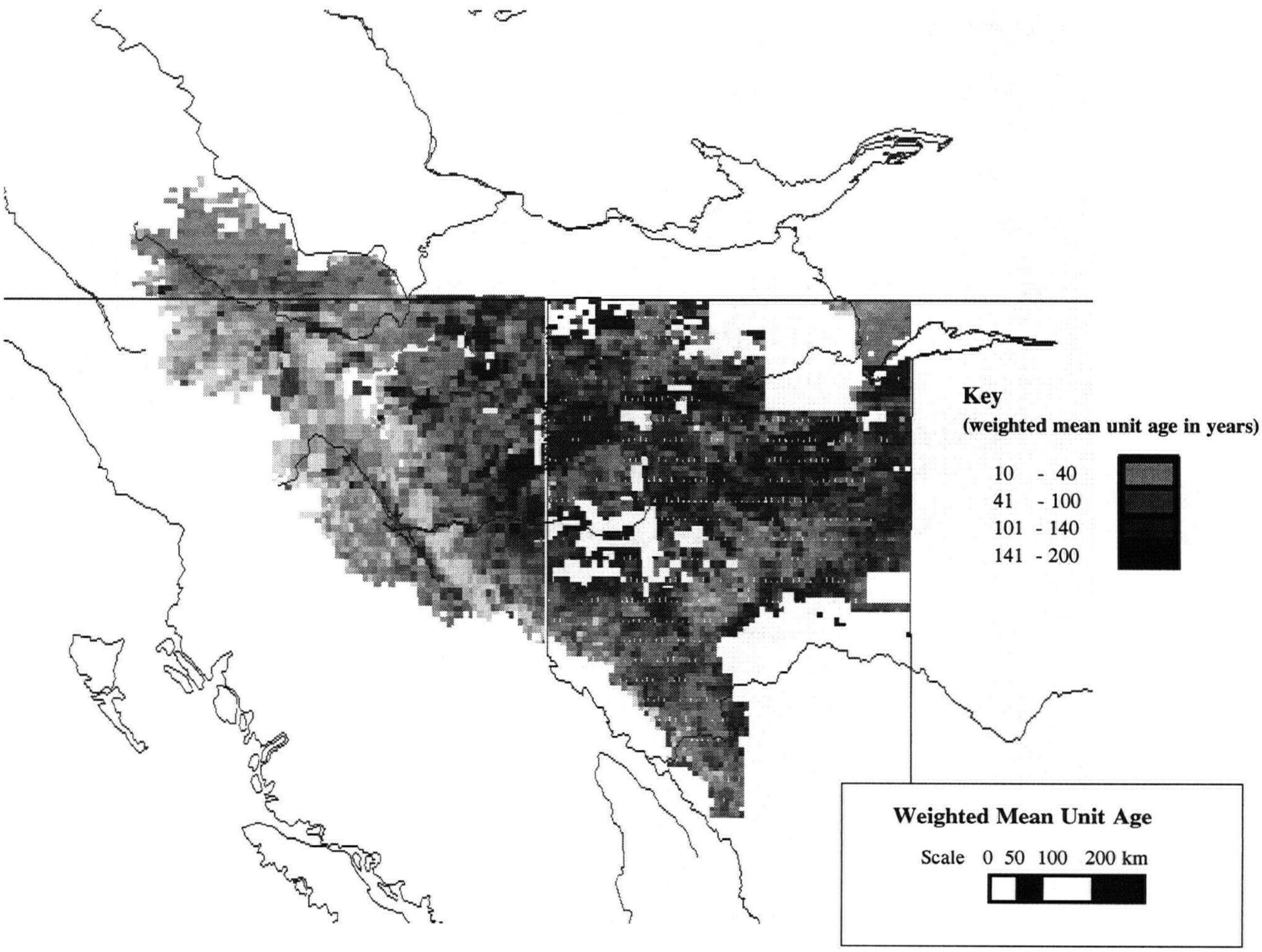


Figure 6. Weighted mean unit age for use in the MBFP model.

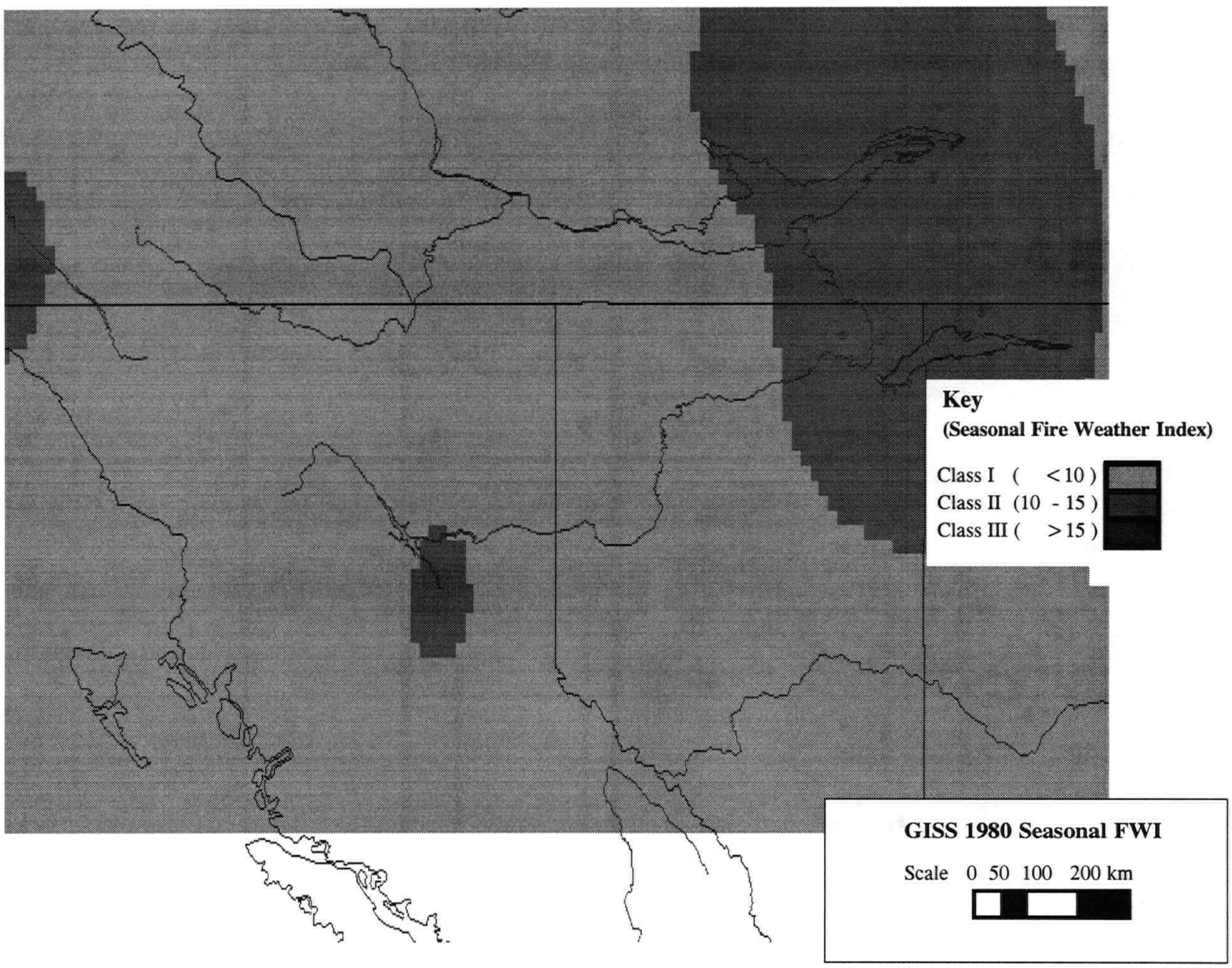
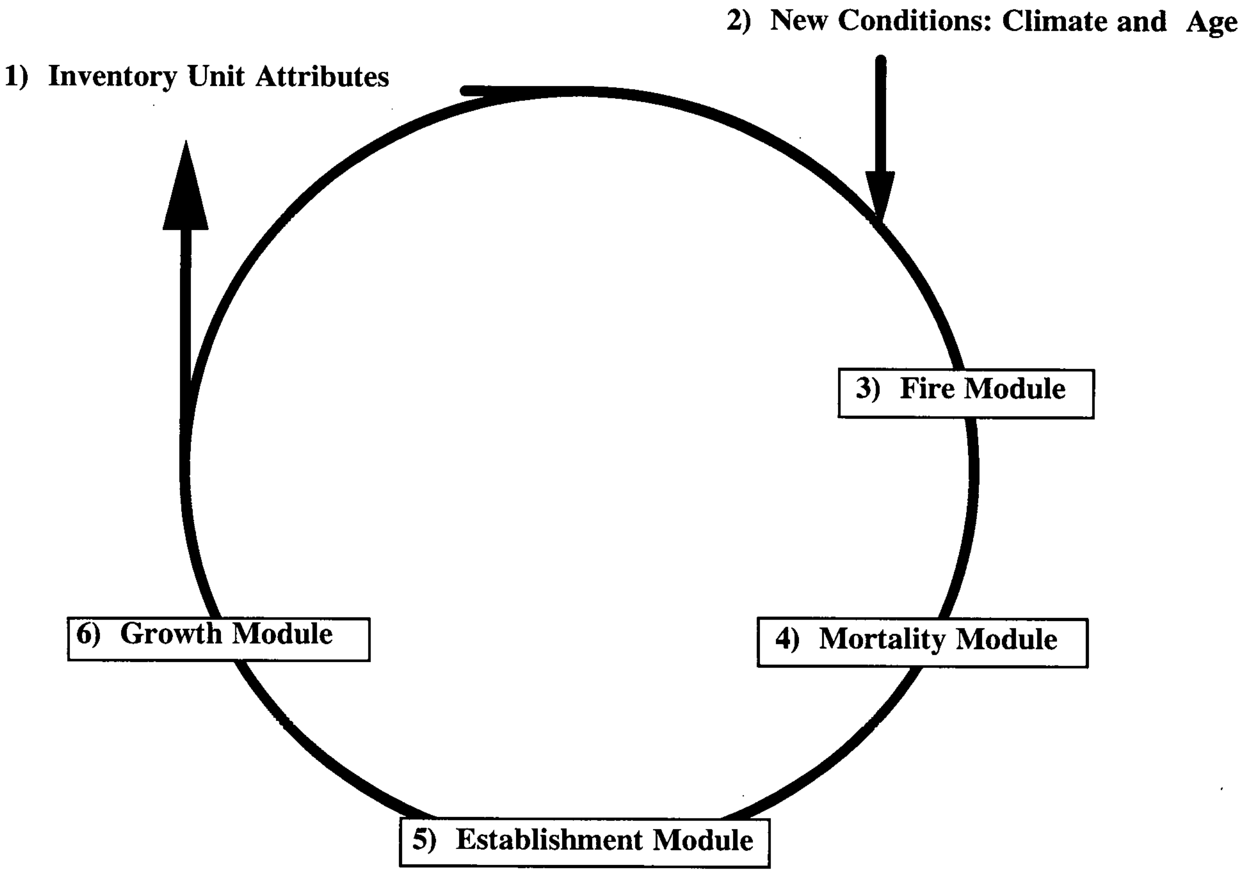


Figure 7. Classified GISS 1980 Seasonal FWI for use in the MBFP model.



1) Weighted mean age; species proportional occupancy; species standing volume.
2) Climate and Seasonal FWI for the current time step; weighted mean age and species agegroups for the current timestep (*i.e.* plus ten years).
3) Possible unit disturbance based on seasonal FWI distribution and seasonal FWI fire frequency.
4) Species age and predicted growth for the climate conditions determine mortality. Unit disturbance occurs once cell occupancy reaches 0.5 or less.
5) Unit age of five years, and species establishment proportions (as determined by climate conditions) assigned for units disturbed by fire or mortality. Merchantable volume removed from the unit, and all species assigned Age Group I.
6) Species growth based on species age group, climate conditions, proportion occupancy and unit area of forested land. Volume generated summed with unit's previous time step value.

Figure 8. The MBFP model cycle of major forest dynamic processes. Each cycle of the MBFP model represents a ten-year time step using GCM scenario climate conditions. Through each time step the inventory units' attributes are changed in value by the module processes, which are sensitive to climate conditions.

the modules is given in Appendix 3). These modules were configured to be easily adjusted and updated for future changes to the MBFP model. Each module was tested separately in a shell run through the GISS GCM scenario conditions to determine the module's validity.

The species growth rates, and the establishment proportions used in the MBFP model, were related to climate through the developed multiple linear regression equations (Chapter 3). These equations were used with the GISS climate raster maps for each time step at a coarse spatial resolution of 15 minutes. Twenty-seven raster map surfaces of establishment proportions, and growth and decay rates through all the age groups in the species' life cycles were generated for each time step for use in the establishment and growth modules.

The relationships built for the MBFP model between baseline 1951-80 climate conditions and forest inventory attributes (as described in Section 3.1.2) are held constant for all GCM scenario runs. As GCM's vary in their ability to represent the present climate processes each must be adjusted to the 1951-80 baseline climate conditions before the MBFP model is run through the GCM climate change scenario. The adjustment would require the difference be taken between the GCM's 1980 base state climate values and the projected climate values at each of the time steps for the GCM. The difference in value for each climate variable would then be summed with the 1951-80 baseline climate values. These resultant climate values for each time step would then be used for all runs made with the MBFP model through the GCM climate change scenario (adjusted to the 1951-80 baseline).

In the MBFP model study area, the GISS GCM consistently had lower mean temperature and precipitation values for the summer months, for the entire scenario period (1980-2050), than the baseline 1951-1980 data. By adjusting GCM's to baseline conditions the MBFP model results can be compared across GCM's as similar base state conditions exist for each GCM.

The change of inventory unit attributes over time within a GCM scenario run is of primary interest. It is the difference between the MBFP model inventory unit values output when run without climate change (using the adjusted GCM 1980 values) and the output when run with climate change (using the adjusted GCM 1980 to 2050 values) that is of interest, as they would have changed in relation to the GCM's climate change scenario. Hence, climatic differences between the baseline (1951-1980) data and the unadjusted GCM (1980) values, are not a major concern.

The four major forest dynamic processes represented by the cycle modules in Figure 8 are described below and discussed in order of occurrence. The source code for these modules may be found in Appendix 3.

Fire Module

The first form of inventory unit disturbance was generated within the fire module, which remains dysfunctional in the MBFP model as a result of an unexpected limitation within the GRASS *r.infer* subshell. Another approach to incorporating fire may be taken that is more supportable through GRASS subshells, or that reconfigures the data for successful subshell entry using unix commands supported in Linux. The initial approach developed for the MBFP model (which is otherwise functional) is described below.

The rules of fire disturbance were established using: (1) the number of units burned within the Mackenzie Basin modelled area in a 10-year time period, based on a disturbance frequency related to the inventory units weighted mean age; (2) classification of seasonal fire weather index (FWI), which indicates fire hazard based on seasonal temperature and precipitation; and (3) a ratio between the area burned and the seasonal FWI class.

Unit disturbance was assumed to involve the loss of the entire standing volume of a unit. The weighted mean age of inventory units for the modeled area of the Mackenzie Basin was 91.46 years. This suggested a 10.9% chance of unit disturbance every ten years. As no other independent disturbances, such as harvesting or insect attack, were included in the MBFP model, the entire unit disturbance frequency was assigned to fire occurrence. No allowance for the allocation of fire disturbance with respect to spread was made in the fire module (as rules were not determined for spread across the variable inventory unit sizes and forested land areas within units); thus, fire disturbance was allocated to units randomly, without accounting for neighbors.

Seasonal FWI values were classified into three categories based on the mean of June, July and August FWI values. Each category represented a hazard level of a randomly distributed fire ignition event causing unit disturbance, with the highest FWI category holding the greatest hazard of unit disturbance. The lowest category for 1951-1980 baseline climate conditions had a mean June, July, and August FWI value of less then 10, the medium category had a value greater or equal to 10, and less than or equal to 15, the highest category of FWI had a value greater than 15. As a result of limitations within GRASS, the FWI categories had to be translated into frequencies of randomly distributed fire ignition events which cause pixel disturbance. Each frequency parallels geographically the seasonal FWI category it represents, and for each category, the number of units to be burned was related to a ratio of area burned-to-seasonal FWI categories. This ratio was based on data from the Fort Smith and Yellowknife climate stations, including their surrounding fire history.[17] It was recognized that this area was not within the MBFP models' geographic region; however, this information was the best available.

[17] The analysis of FWI to area burned for Fort Smith and Yellowknife were performed by Lisa Kadonaga, Graduate student, University of Victoria, Victoria.

The pixel disturbance caused by the randomly distributed fire ignition events had to be transformed to unit disturbance, as units were represented by many pixels, and analysis was kept at the unit level. The transformation required the use of inference, which is limited in the *r.infer* subshell to 100 inferences per subshell run. The unit disturbance rate of 10.9% per ten-year time step under no climate change conditions was not possible for the entire modelled area with the *r.infer* limitation, as 728 units (of the 6683 units modelled) were required for disturbance per time step. However, this approach does work for modelling smaller areas which require less than 100 units disturbed per time step under no climate change conditions (an area with 918 units or less for example). Nevertheless, the expected increase in the rate of unit disturbance under climate change conditions[18] could exceed the *r.infer* limitation for the selected smaller area as well. Other approaches to incorporating fire disturbance in the model were examined, but were considered beyond the scope of this work.

Mortality Module

The second form of inventory unit disturbance was generated within the mortality module, as defined by species age and productivity under the current climate conditions. Each species was assigned a range of productivity at Age Group III, divided into three categories of poor, medium and good (Table 9).[19] Age Group III was chosen for classification purposes because established mature stands likely had better inventory data to be referenced for determining growth response then young or older stands. Any species with a unit age that places it in Age Group III or greater, and that also had a poor productivity (as predicted by climate parameters), would be defined as dead. The species

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[18] Under climate change conditions the geographic distribution of FWI categories would change, causing a change in fire disturbance of units over the modelled area.

[19] These categories of species productivity were defined by Peter Marshall (Associate Professor, Forest Resources Management Department, University of British Columbia) for pure stands of each species in order to relate to the Adjusted MDI values produced from the growth regression equations developed in Chapter 3.

occupancy for that unit would then be transported to a raster map-layer representing the unit's proportional occupancy by dead species. When 50% or more of the unit occupancy consisted of dead species, it was considered disturbed, the standing volume of all the species would then be removed, and the unit opened for establishment.

Table 9. Classification of species productivity at Age Group III for use in determining species stress-induced mortality.

Species in Age Group III	Poor Growth (in m^3/ha/decade for pure species, even-aged stands)	Medium Growth (in m^3/ha/decade for pure species, even-aged stands)	Good Growth (in m^3/ha/decade for pure species, even-aged stands)
Black Spruce (120 - 200 years)	< 6.0	6.0 - 14.0	> 14.0
White Spruce (120 - 200 years)	< 6.0	6.0 - 14.0	> 14.0
Pine (80 - 120 years)	< 6.0	6.0 - 14.0	> 14.0
Trembling Aspen (70 - 80 years)	< 5.0	5.0 - 17.5	> 17.5
Paper Birch (70 - 80 years)	< 5.0	5.0 - 17.5	> 17.5

This crude method of assigning mortality was the result of previous decisions on the aggregation of inventory data. Improvement to the mortality module may be possible with the addition of the standing volume of dead species, and partial unit regeneration.

Establishment Module

Re-establishment proportions for a unit after disturbance was calculated using the relationships between proportional occupancy and climatic factors developed in Chapter 3. After unit disturbance by fire or mortality (50% or more of the area comprised of dead trees), the establishment module would reset the unit with a new species composition (which is dependant only on the current climate values) and assign a zero value to the volume of each species within the unit, as well as to the proportion of mortality. Unit age would be set at the time steps' midpoint of five years, and each species would be assigned to the first Age Group for determining growth rates. New species proportions assigned to the disturbed unit were derived from the establishment proportion relationships described in Chapter 3.

Growth Module

The growth module, as the final step in the MBFP model cycle, would then be executed, as all units would now hold the current age, species proportions, and volumes. The previously generated adjusted MDI map-layers for growth rates for each species in each age group are sourced to determine productivity values. These values are then adjusted for application to units with variable species proportions, and forested areas, by multiplying each species' MDI value by the proportional occupancy of that species and the number of hectares of forested land within the unit. The volumes produced (positive or negative) by each species within the time step are then added to the standing volume for that species within the unit, with a separate record kept for MBFP model analysis. If a species has its volume reduced in the time step to be less than or equal to zero, then the proportion of the unit occupied by that species is assigned to the raster map layer representing proportion of dead species.

After a cycle through these four modules, each unit will have had: (1) a chance of being burnt; (2) each species tested for climatic stress (poor productivity, and Age Group III or greater) and possibly killed; (3) the chance of being regenerated (in the case of fire or cumulative mortality leading to unit death); and (4) growth in the volume of each species present. The new unit values are then cycled through the modules again, using the climate conditions predicted for the next decade. After all the cycles through the climate scenario have been completed, changes in the inventory unit attributes over time can be assessed.

If the MBFP model was run with no climate change introduced, the mean age of the inventory units for the study area would be expected to remain similar to the mean age of the initial inventory units, as the frequency of fire disturbance would be similar to the 1980 base state climate conditions after the calibration of the MBFP model for the GCM scenario. However, the distribution of unit attributes after a no climate change scenario run of the MBFP model would differ from the initial inventory units as a result of the model equilibrium assumptions (fire frequency, mortality, establishment). The age distribution would be expected to approach a negative exponential curve as the equilibrium state rather than the present distribution of boreal forest ages, which is the result of many factors, such as fire suppression, harvesting insect attack and inventory bias.

Under climate change conditions, the distributions would be expected to change in relation to the increased disturbance frequency (through both fire and mortality) caused by the warmer climate. Average unit age would be expected to decrease; however, the changes in species' proportions and growth rate are more difficult to predict, as their relationships with climate would react differently over the landscape.

Sensitivity Analysis

A series of nine scenarios for the MBFP model, involving a 10% change in the values of both the fire and growth modules, were prepared as an example of a sensitivity analysis (Table 10). After multiple runs of the MBFP model are performed for each scenario to reduce noise in the results, comparisons among scenarios could be made. Tables of the change over time in each scenario in terms of 1) overall unit age distribution, 2) percent of area burned, 3) species standing volume (stratified by the species and their age groups), and 4) species proportional occupancy (stratified by the species), would be useful for scenario comparison. The overall change associated with each scenario could be further stratified by geographic regions, such as those shown in Figure 9. These four regions (the Rockies, Hay River/Upper Laird, eastern Boreal, and Southern Peace River) were developed using topography and Rowe's (1972) forest regions. In this manner, the MBFP model could be assessed for changes in forest composition under climate change, and the model's fire and growth modules could be tested for sensitivity to change in their variables. Further module sensitivity tests could be performed on mortality by varying the level of MDI at which stress is determined, and the age at which stress is considered fatal.

Table 10. Sensitivity analysis for the fire and growth modules, scenario identification.

	Percent Burned Area of the Mackenzie Basin (over a ten year period without climate change, used for MBFP model calibration)		
Calculated Species Growth Rate	Low (9.8 %)	Medium (10.9%)	High (12.0%)
Species Calculated MDI, less 10 %	1	2	3
Species Calculated MDI	4	5	6
Species Calculated MDI, plus 10%	7	8	9

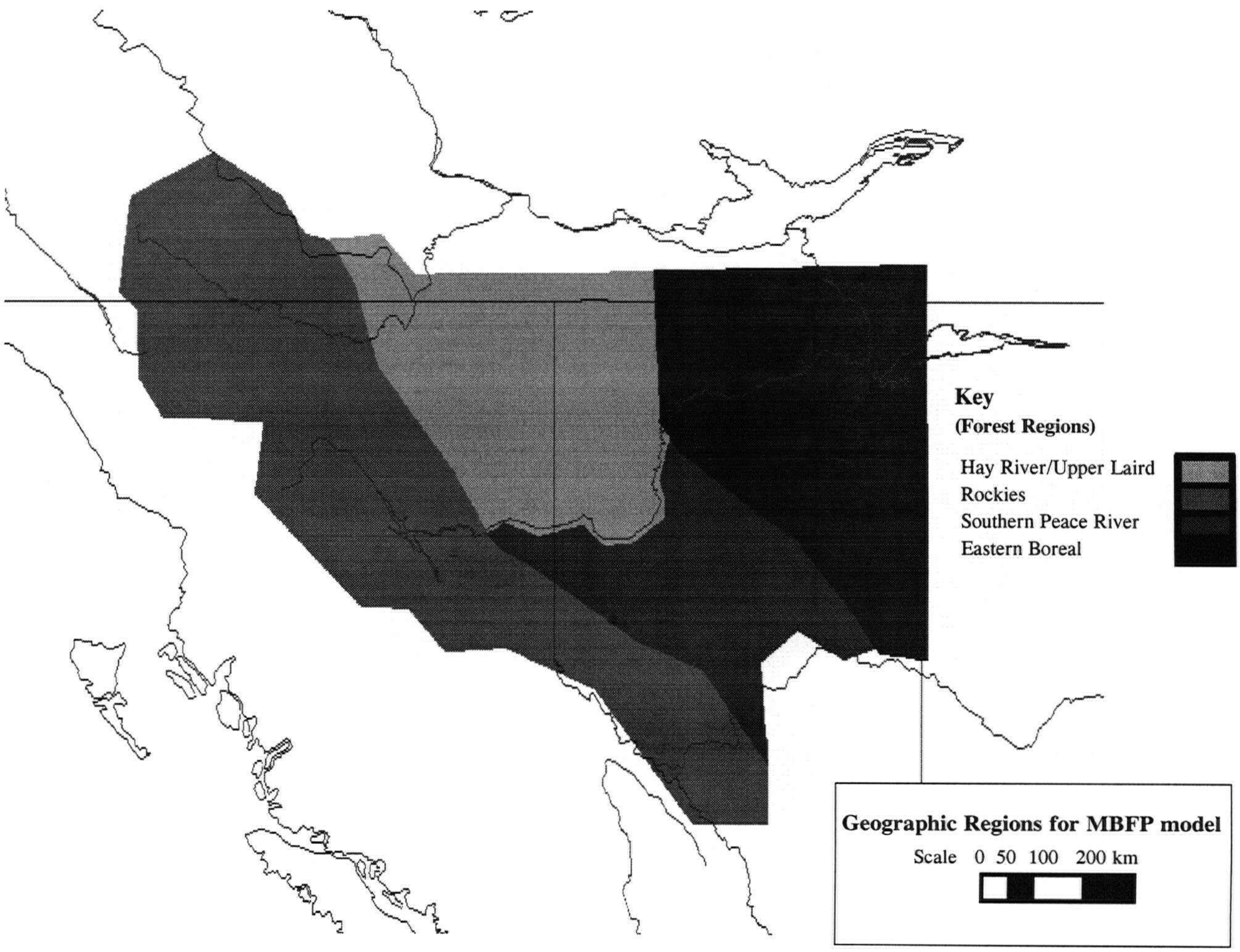

Figure 9. Geographic regions for stratification of the modelled Mackenzie Basin forest inventory.

4.2 Discussion

The MBFP model was built to relate simple forest dynamic processes to climate conditions using a GIS environment. The GIS was valuable for its ability to store data at raster pixel centroids, which could then be sourced for different scales of raster map analysis. However, the geographic assignment of forest inventory data was limited to the forest inventory unit, as the only spatial attribute of stand records was their inventory unit location. This limitation precipitated the synthesis of forest inventory unit data into mean unit values, which were then used in all further analyses of forest-to-climate relationships. The raster map-layer method of data storage was selected because of the advantages for incorporating varying data input scales from the forest inventory and the climate data from the GCM. The GRASS programmable shell used in building the MBFP model required all data to be in single attribute raster map-layers. The use of multiple attribute vector polygons would be preferred for some processes; however, GRASS shell programming functions are predominantly raster based, thus dictating the form of GIS data storage.

The simple forest dynamics model presented here does not take advantage of the spatial relationships made possible in a GIS environment. Spatial processes such as fire spread and seed source location could be added to the MBFP model with relative ease, once rules for these processes were determined. The base unit of model analysis could have been kept at the original stand-level records if the MBFP model was written for a different environment (*e.g.*, a spreadsheet). The limitation of a single geographic location per inventory unit would not affect data processing, and maintaining stand record data would reduce the loss of inventory information which occurred when the scales were changed. However, processing of the large stand-level database would create technical difficulties, as some files were over 40 MBytes in size. The amalgamated forest inventory database with mean unit values was easily manipulated in PC SAS for the generation of climate relationships. The advantage of PC data processing, co-ordination of analysis platforms with fellow MBIS researchers, and the future possibilities provided by the GRASS GIS environment, meant that the GRASS environment was the preferred modeling tool, with additional spreadsheet support for data analysis.

The climate relationships generated in PC SAS for predicting establishment and growth by age groups for the five species (Chapter 3) were used in the MBFP model for updating the inventory in relation to climate conditions. These relationships are equally valid for use with any GCM climate change scenario, as they were calculated using baseline climate values from weather station data interpolation, and are therefore not GCM-specific. Other environmental factors, such as site quality, typically included in inventory updating modules, were not used since they were not available in the database. Allowing mortality to be caused by climate stress, and fire frequency to be determined by seasonal climate conditions, allowed further climate interaction with forest inventory prediction. Other possible climate interactions with the forest inventory were not represented in the MBFP model; however, inventory interactions with soil development, species migration, increased insect outbreak, and cloud cover could be included with future improvements in this area of study.

Chapter 5 General Discussion and Recommendations

There is little known about the causes of past and present global climate change; the variety of hypotheses used in predicting global conditions reflects this. The few experimental platforms available to mimic the global climate system have resulted in an array of predictions which are scale dependent and are usually produced at a coarse resolution. Regional predictions are considered to be inaccurate, and it has been argued that such predictions are therefore not appropriate as the basis of further research (O'Neill *et al.*, 1988; Turner *et al.*, 1989). However, for the prediction of climate change impacts on individual species, species-to-climate relationships must first be identified, and in this way, concurrent research at various scales is effective.

5.1 The Importance of Data and Scale in Modelling Systems

The scale of an investigation depends on the purpose of the study, and the detail of the data available. There are many resolutions and scale limitations in source data. Large-scale predictions frequently depend on in-depth studies of fine resolution, small-scale relationships, which require transition across scales. However, small-scale phenomena may change in behaviour over larger scales, and therefore caution is necessary when developing predictive theories across scales (King, 1990).

Forest descriptions range from national inventories[20] to individual stand and tree records. Climate descriptions are based on records from weather stations, and atmospheric behaviour and regional conditions. The resolution and quality of forest and climate data, and the scales they cover, did not converge for this study; therefore, transfer of information across scales was required. The concern is great that scale transfer may exceed a critical threshold (beyond which the relationships built for the MBFP model are no longer valid); this phenomenon has been recognized in other studies of this kind

[20] National forest inventories are generally based on low intensity ground sampling and may be based solely on remote sensing techniques for isolated regions and areas of low productivity.

(King *et al.*, 1988; Turner *et al.*, 1989). Change may not be found in the character of a relationship, but in the relative importance of the relationships within the model. There is no single correct way to transfer data across scales. In the process of scaling up, details will be lost from the original information. In the process of scaling down, assumptions must be made to develop a framework for the new level of information generated. Through either process, some quality may change, making the new scale biased in its representation of the original information.

The variety of inventory unit sizes used in the Canadian Forest Inventory, and the records that fit the information requirements for this study, helped to generate the relative productivity unit for forested land (weighted mean m^3/ha/10 years for each species within an inventory unit) used in Chapter 3. However, weighted averages do not always produce reasonable measures, because heterogeneity may influence processes in non-linear ways (King *et al.*, 1988). The aggregation of stand records in an inventory unit to a single age value, and a volume value per species, is assumed here to be representative of that unit's productivity. Further manipulation of the base data could be performed for other studies where even-sized units are needed. Spatial relationships such as fire spread and migration are better represented in models over an area with equal sized units. In this study, neither of these spatial relationships was used, and the variety of inventory unit sizes was retained in the MBFP model's base data set.

5.2 Modelling of Systems

Forest simulation models can only represent the quantifiable characteristics of known forest properties and processes. There are many species-to-climate relationships, species inter-relationships, and individual species processes which are not understood. Without this understanding, species survival and regeneration through competition and changing environmental conditions cannot be adequately projected. There have been many examples where a change in species success has been traced to a relationship which was previously overlooked or ignored because of its apparent insignificance. The importance of fungi (in symbiotic mycorrhizal associations) to the nutrient gathering processes for some tree species is such an example. Improved survival rates for planted nursery stock was found after the adoption of inoculating the soil with mycorrhizal-forming fungi (Kimmins, 1987). Caution must be used with model development and interpretation, as deficient comprehension of the relationships and processes represented can cause inaccurate interpretations.

As part of model construction, the form of representation for different processes and relationships must be chosen from among empirical assumptions (where the present species-to-climate relationships are considered to be in equilibrium), deterministic rules (where limits and levels are assigned to interactions), dynamic forces (where changes are induced based on a probability distribution over an area), and constants. The initial conditions within the study must also be selected before any predictions are made, and should be considered when the results are presented. This is important since initial assumptions put the results in context and help differentiate models.

Of the many approaches possible for the prediction of species productivity through climate change, the simplistic MBFP model described in Chapter 4 was developed. It was based on the availability of the data, its scale, and the tools accessible for the project. In such large-scale modelling, only major natural forces were considered in relation to forest productivity. Each of the five species was treated individually, and climate relationships were determined for the forest processes of growth, mortality, establishment and fire. The influence of soil types on species growth and establishment was not included in the MBFP model for three reasons: (1) predictions of change in soil types with climate change are not currently available, (2) the data were not available from the national inventory, and (3) the time scale of such change is far longer than the time-period of interest to this study, making the relationships irrelevant to the projection of forest productivity through climate change scenarios over the present time horizon.

In its present form, the MBFP model has one flaw which must be addressed before results can be produced. The flaw concerns the application of fire, which needs to be modified to meet the limitations of GRASS. The modular components of the MBFP model can be adjusted to accommodate changes for any process as required. This flexibility allows for easy incorporation of any future improvements to the model.

The MBFP model has been based on a non-human dominated world, with the physical environment-to-species relationships being considered exclusively. In any climate change scenario, socio-economic demands on the land will also change (Dale and Rauscher, 1994). The growing human population and its skills in manipulating land productivity will have an effect on the forested areas modelled. These impacts may be projected by other members of the MBIS, and incorporated into the present MBFP model.

It should be remembered that the difficulty of representing dynamic systems with a model is the number of processes and relationships from the "real world" that will inevitably be missed. With the absence of these unrecognized or unmeasured processes, the assumption is implicitly made that they have no cumulative effect on the system. However, the model lacks their contribution to the system's sensitivity and resilience. Of the processes and relationships included in a model, values will have to be assigned for ranges, parameters and constants. Values recorded from previous studies are limited in their representation of a process or relationship by the area they were taken from, and conditions at those locations. Competition and tolerance of species vary with many factors, and the realized niche of each species available for measure (and input to models) is only a subset of the fundamental niche.

Many of the forest-to-climate relationships developed for models assume the present species distribution is at equilibrium with the climate, and allow no alteration due to human activity. However, the practice of fire suppression has altered the forest's age structure, and species composition. In this way, values held constant in models may misrepresent the range for the process or relationship for which they were derived. Other sources of value determination would be possible through estimation or use of another model's output.

5.3 Complexity in Models

There are several drawbacks to having complex models. Increasing the level of complexity incorporated into a model usually requires more parameter values, and increases the likelihood that there will be insufficient data available to estimate these parameters. Parameter estimation must then be employed, increasing the uncertainty of the model output (Bugmann and Martin, 1995). Also, the range of data available for highly complex models is usually limited by physical, as well as economic, restrictions on data collection. The specificity of a complex model's results makes them less translatable to other scales or locations, and difficult to evaluate through comparison with other models.

The scale of a model (as previously discussed) is determined by the purpose of its design, and the tools and data available. For forest system predictions, there have been many models developed over a range of scales. For management purposes, landscape and regional scale models have been favoured for impact assessment of various environmental change scenarios (Dale and Rauscher, 1994). One example of a landscape model is the Holdridge Life Zone classification, where the distribution of major ecosystem complexes were related to the mean annual climate conditions over North America (Holdridge *et al.*, 1971). The Holdridge model assumes that the vegetation complexes identified are at equilibrium, that their species composition remains constant throughout their classified range, and that they are distributed solely on the basis of climate conditions. This model's simplicity and coarse scale were used to cover continents with predictions. A higher level of complexity for forests, in both input and model analysis, is found in the JABOWA/FORET family of vegetation dynamic models (Shugart, 1984). These community-level forest models represent species independently with temperature, moisture, light and nutrient parameters for their regeneration, growth and death sensitivities. Species composition, size, and age distributions are also kept available for assessment of model runs through climate change scenarios. These models have been widely used for studies throughout North America and in other temperate forests of the world (Shugart *et al.*, 1992). They were the first to predict dramatic shifts of species range in response to changes in the climate using the finer resolution of community models.

The MBFP model lies between the continental and community forest model approaches. It uses a coarse scale with a moderate level of complexity to cover a large subcontinental area. The MBFP model is flexible, and may be more useful for forest-related studies that span regions than continental or community forest models.

5.4 Recommendations

Each model created for prediction is only as strong as the weakest assumption within it. This statement makes model results appear less important, and increases the focus on the methodology used to generate predictions. It is this methodology which carries the value of the researchers' work and experience, as it is their interpretation of the relationships and values commonly available to describe a system. With improvement to the number and quality of values available for modelling, assumptions may be reduced, and model strength improved.

Progression in the development and improvement of models is dependent on the researchers and data available. The MBFP model described in Chapter 4 was developed for a large area at the variable scale of forest inventory units, using a moderate level of complexity. It was designed to run with different GCM climate change scenarios, which would be recommended for a broader analysis of the model results. The MBFP model still requires a functional fire module before it can be tested. Calibration of the model to a GCM scenario and the analysis of the model run results would then follow.

The values used in the MBFP model were derived from the national forest inventory for merchantable volume, which does not consistently include records for non-commercial species or young stands. An improvement would be to gain access to an inventory of the research area that would include all tree species, with age classification for each stand, soil types, and land classification for all unforested areas. The methodology for developing species-to-climate relationships could be enhanced through stratification by soil type, and improved representation by the younger age groups. The likelihood of this information being made available for an area as large as the Mackenzie Basin in the near future is low, as the provincial and territorial governments would be required to develop the inventories first.

Stand disturbance information (*e.g.*, frequency and size of fire and insect outbreak) would be valuable for the interpretation of species establishment success after disturbance. Information on the dynamics of species invasion into non-forested land, and species decline within forested land would be valuable for interpreting the rate of border movements for the boreal forest in relation to changing climate conditions. These components of the forest system are not satisfactorily addressed in the MBFP model, and could be greatly improved upon. Fuel loading and fire sensitivity, as they vary with stand age and FWI, respectively, would assist in the development of fire spread probability and spatial allocation of fire disturbance. Recognition of the variation in species growth with provenance, and its incorporation in the growth equations used in the MBFP model as a stress on established species that suffer climate change, may be accomplished when more information is available. The invasion of new species and subsequent changes in community composition would be another useful addition to the MBFP model. Initial species suggested for investigation would be Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and Engelmann spruce (*Picea engelmannii* Parry).

5.5 Summary

A methodology for predicting the forest species productivity and establishment proportions using climate parameters has been developed in this work. The influence of climate on species growth has long been recognized and, with the use of climate station data interpolated over forest inventory records, relationships may be developed. The national forest inventory stand-level records were refined, and aggregated up to the inventory unit-level. The productivities of the predominant five species (stratified by age groups) and establishment proportions within inventory units were then related to selected climate variables through stepwise regression procedures. These relationships were used in the MBFP model to drive the species-specific productivity trends through climate change scenarios.

The MBFP model functions through climate change scenarios in ten-year time step cycles. Modules representing the effects of fire disturbance, stress-induced mortality, species establishment and species productivity are applied within each cycle for the duration of the climate scenario.

Suggestions for improvements to the MBFP model were made. The most pressing of these is to modify the fire disturbance module to overcome the limitations of the GRASS environment. The modular structure of the MBFP model will allow easy implementation of any improvements. Once the MBFP model is fully functional, it could be used in socio-economic or other studies as part of the MBIS collaborative work.

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Appendix 2 Coefficients for the species productivity and proportion regresstion equations by Age Group.

Table of Regression Selected Variables	Black Spruce	Coefficients for the Regressions		
Age Group (Species Specific)	I (0 - 50)	II (51 - 120)	III (121 - 200)	Proportion
JAN1980T (January 1951-80 Temp.)			0.7032465	0.017533773
MAY1980T (May 1951-80 Temp.)				1.10967686
JUN1980T (June 1951-80 Temp.)			-6.1346701	0.091287551
AUG1980T (August 1951-80 Temp.)	0.837723224		18.3096651	-0.51030352
SEP1980T (September 1951-80 Temp.)			-5.4459840	0.050502134
OCT1980T (October 1951-80 Temp.)				0.037669722
APR1980P (April 1951-80 Precip.)	0.455995788		-0.3612497	-0.0026862120
JUN1980P (June 1951-80 Precip.)				-0.00065904614
SEP1980P (September 1951-80 Precip.)		-0.357499100		0.0078655814
OCT1980P (October 1951-80 Precip.)				-0.0065316897
TOTPSUMR (Total Summer Precip.)	-0.0681011550		0.07936509	
MANNPRCP (Mean Annual Precip.)		0.662551775		
APR1980E (April 1951-80 ETp.)		0.275865770	0.2771189	0.028269124
MAY1980E (May 1951-80 ETp.)				-0.20027014
AUG1980E (August 1951-80 ETp.)			-4.6082135	0.11550856
OCT1980E (October 1951-80 ETp.)		-0.468516915	-0.4918582	0.021201257
ANN1980E (Annual 1951-80 ETp.)				-0.037949464
Number of Variables Included	3	4	9	15
Intercept	8.933652285	6.001300696	255.0480676	11.43982730
Number of Observations (N)	151	4588	401	6418
R^2	0.148846	0.438072	0.374951	0.318008
$(MSE_e)^{1/2}$	4.888262	3.080214	3.355467	0.085678

Table of Regression Selected Variables	White Spruce		Coefficients for the Regression	
Age Group (Species Specific)	I (0 - 50)	II (51 - 120)	III (121 - 200)	Proportion
JAN1980T (January 1951-80 Temp.)	-1.62907866	-0.8024511	0.747379153	0.0457164699
MAY1980T (May 1951-80 Temp.)		-19.8180388		0.0989195621
JUN1980T (June 1951-80 Temp.)		-1.4954454		
AUG1980T (August 1951-80 Temp.)		8.5777031		-0.250130554
SEP1980T (September 1951-80 Temp.)		2.7061377		0.169224788
OCT1980T (October 1951-80 Temp.)		-1.2253510	-2.053763395	-0.193215631
APR1980P (April 1951-80 Precip.)	0.52632642	-0.108938		
JUN1980P (June 1951-80 Precip.)				-0.0246653225
SEP1980P (September 1951-80 Precip.)	-0.59858599	-0.4043351	-0.233048593	-0.00998765922
OCT1980P (October 1951-80 Precip.)		-0.2305938	-0.192167749	0.00345528093
TOTPSUMR (Total Summer Precip.)				0.00682435445
MANNPRCP (Mean Annual Precip.)	1.20747657	1.3105943	0.562423821	
APR1980E (April 1951-80 ETp.)			0.166456089	
MAY1980E (May 1951-80 ETp.)		3.1594379	0.684212827	
AUG1980E (August 1951-80 ETp.)		-1.9090016		0.0558317351
OCT1980E (October 1951-80 ETp.)		-0.7368680	-0.478672854	0.00929460841
ANN1980E (Annual 1951-80 ETp.)		0.4915950		
Number of Variables Included	4	14	8	11
Intercept	-49.87079984	-167.4196501	-6.201869669	-1.684347465
Number of Observations (N)	173	5304	916	6418
R^2	0.098041	0.459068	0.304120	0.246856
$(MSE_e)^{1/2}$	5.833911	3.468747	3.340883	0.176945

Table of Regression Selected Variables	Pine	Coefficients for the Regression		
Age Group (Species Specific)	I (0 - 40)	II (40 - 80)	III (81 - 120)	Proportion
JAN1980T (January 1951-80 Temp.)	-1.86841417	-1.531757905	-0.659930125	-0.0367397389
MAY1980T (May 1951-80 Temp.)			-2.706399573	
JUN1980T (June 1951-80 Temp.)		-5.423146492	-2.403608310	-0.0640391414
AUG1980T (August 1951-80 Temp.)				0.410209108
SEP1980T (September 1951-80 Temp.)		8.030356972	5.582590220	-0.197486193
OCT1980T (October 1951-80 Temp.)			-3.146741048	0.245567381
APR1980P (April 1951-80 Precip.)		-0.294666898		-0.00689593405
JUN1980P (June 1951-80 Precip.)			-0.404155115	0.019409975
SEP1980P (September 1951-80 Precip.)		-0.289898159	-0.651445995	0.00714102884
OCT1980P (October 1951-80 Precip.)			-0.240085969	0.0132078599
TOTPSUMR (Total Summer Precip.)	0.089434451		0.129033795	-0.00422645320
MANNPRCP (Mean Annual Precip.)		0.771394601	1.250733486	-0.0249773138
APR1980E (April 1951-80 ETp.)		0.478108682	0.574783703	
MAY1980E (May 1951-80 ETp.)		-0.575329816		-0.0605581464
AUG1980E (August 1951-80 ETp.)				-0.107699689
OCT1980E (October 1951-80 ETp.)		-0.612468499	-0.338535289	
ANN1980E (Annual 1951-80 ETp.)				
Number of Variables Included	2	9	12	13
Intercept	-54.10266881	9.386932579	-8.618670278	7.912776962
Number of Observations (N)	68	2238	3073	6418
R^2	0.308237	0.334859	0.476312	0.297349
$(MSE_e)^{1/2}$	5.146033	3.856926	4.040839	0.177783

Table of Regression Selected Variables	Trembling Aspen		Coefficients for the Regression	
Age Group (Species Specific)	I (0 - 30)	II (31 - 70)	III (71 - 80)	Proportion
JAN1980T (January 1951-80 Temp.)		-0.3137668		-0.0341932749
MAY1980T (May 1951-80 Temp.)		1.7912406		
JUN1980T (June 1951-80 Temp.)		2.4290324		-0.0541458365
AUG1980T (August 1951-80 Temp.)		-19.9012739	0.510107986	
SEP1980T (September 1951-80 Temp.)		9.4834100	4.998227931	
OCT1980T (October 1951-80 Temp.)			-4.425585286	-0.114585832
APR1980P (April 1951-80 Precip.)			-0.524642831	0.00836080627
JUN1980P (June 1951-80 Precip.)				
SEP1980P (September 1951-80 Precip.)		0.04669654		-0.00860668391
OCT1980P (October 1951-80 Precip.)	0.6091570094	0.07273100		-0.00749024290
TOTPSUMR (Total Summer Precip.)				
MANNPRCP (Mean Annual Precip.)			0.497167832	0.0166649743
APR1980E (April 1951-80 ETp.)			0.451198157	0.00683689305
MAY1980E (May 1951-80 ETp.)			-0.761532066	0.0356063579
AUG1980E (August 1951-80 ETp.)		4.7195604		0.0112027760
OCT1980E (October 1951-80 ETp.)		-0.3028311		0.00787431032
ANN1980E (Annual 1951-80 ETp.)				
Number of Variables Included	1	9	7	11
Intercept	-0.0005793771	-223.5283964	0.185213169	-2.659277191
Number of Observations (N)	16	1440	897	6418
R^2	0.275913	0.129611	0.307677	0.408470
$(MSE_e)^{1/2}$	4.537059	3.432133	3.096302	0.157795

Table of Regression Selected Variables	Paper Birch		Coefficients for the Regression	
Age Group (Species Specific)	I (0 - 30)	II (31 - 70)	III (71 - 80)	Proportion
JAN1980T (January 1951-80 Temp.)			-0.56918917	
MAY1980T (May 1951-80 Temp.)			-2.85265510	
JUN1980T (June 1951-80 Temp.)		-1.74579473		
AUG1980T (August 1951-80 Temp.)				
SEP1980T (September 1951-80 Temp.)		1.91452706		
OCT1980T (October 1951-80 Temp.)		7.13043330	5.80328606	-0.02592927624
APR1980P (April 1951-80 Precip.)		-0.52657625	-0.44507693	0.1143678221
JUN1980P (June 1951-80 Precip.)	-0.9965459	-0.11349929	-0.066192409	
SEP1980P (September 1951-80 Precip.)			-0.18628619	
OCT1980P (October 1951-80 Precip.)				-0.002333500416
TOTPSUMR (Total Summer Precip.)				-0.0002921717267
MANNPRCP (Mean Annual Precip.)		0.54628858	0.61780927	0.004533873697
APR1980E (April 1951-80 ETp.)			0.41823122	
MAY1980E (May 1951-80 ETp.)	5.6878562			0.003708982991
AUG1980E (August 1951-80 ETp.)				
OCT1980E (October 1951-80 ETp.)		-1.35394480	-0.96217542	0.002119279989
ANN1980E (Annual 1951-80 ETp.)				
Number of Variables Included	2	7	9	7
Intercept	-241.9865032	20.48495284	19.59111411	-0.1990750638
Number of Observations (N)	16	1299	813	6418
R^2	0.432157	0.109904	0.219508	0.142330
$(MSE_e)^{1/2}$	3.672759	3.532350	3.457824	0.031107

Table of Regression Selected Variables	Stand	Coefficients for the Regression	
Age Group (Species Specific)	I (0 - 40)	II (41 - 100)	III (101 - 140)
JAN1980T (January 1951-80 Temp.)	-2.9387888	-0.52381391	
MAY1980T (May 1951-80 Temp.)		-4.46886256	-1.80672290
JUN1980T (June 1951-80 Temp.)			
AUG1980T (August 1951-80 Temp.)			
SEP1980T (September 1951-80 Temp.)		4.56690312	3.74206439
OCT1980T (October 1951-80 Temp.)		-1.40912707	-5.62265268
APR1980P (April 1951-80 Precip.)		-0.32676022	
JUN1980P (June 1951-80 Precip.)		0.08203966	-0.26298998
SEP1980P (September 1951-80 Precip.)		-0.21350849	-0.50186239
OCT1980P (October 1951-80 Precip.)		0.12760740	-0.48519427
TOTPSUMR (Total Summer Precip.)			0.05340470
MANNPRCP (Mean Annual Precip.)	1.1552732	0.47161020	1.42874151
APR1980E (April 1951-80 ETp.)		0.39118161	0.41093004
MAY1980E (May 1951-80 ETp.)	0.6866356		
AUG1980E (August 1951-80 ETp.)			
OCT1980E (October 1951-80 ETp.)		-0.31626857	
ANN1980E (Annual 1951-80 ETp.)		0.09604608	
Number of Variables Included	3	12	9
Intercept	-130.5108770	-42.27865913	-12.74444596
Number of Observations (N)	68	4130	1852
R^2	0.468836	0.455257	0.442032
$(MSE_e)^{1/2}$	5.301257	3.124752	3.511330

Appendix 3 Mackenzie Basin Forest Productivity Model Code

```
#!/bin/sh
# Written by Isobel Booth begun May 29, 1995.   [mother.sh]

### This is the main shell that will tie all the others together.
# (Inventory units are refered to in the code as "townships", and are represented
# by many smaller "cells" also refered to as pixels in the text of the Thesis)

# Setting the region, and scale for coarse calculations with climate values
g.region mbis.coarse.scale
d.erase

### Creates for all timesteps: fire hazard/frequency layers of Low, Medium and High,
# species regeneration proportions, and growth values for Age Groups 1-4.
fwi.layers.sh
regen.prop.sh
MDIAj.group.sh
r.mapcalc "flat=1"

# Setting the region and scale for fine calculations with forest inventory.
g.region mbis.forest
d.erase

# Setting the base values for the model
r.mapcalc "age.1980=age"
r.mapcalc "bsvol.1980=bsvol"
r.mapcalc "spvol.1980=spvol"
r.mapcalc "pivol.1980=pivol"
r.mapcalc "trvol.1980=trvol"
r.mapcalc "pbvol.1980=pbvol"
r.mapcalc "pdead.1980=0"
r.mapcalc "pdead.1990=0"
r.mapcalc "pdead.2000=0"
r.mapcalc "pdead.2010=0"
r.mapcalc "pdead.2020=0"
r.mapcalc "pdead.2030=0"
r.mapcalc "pdead.2040=0"
r.mapcalc "pdead.2050=0"

l=1980
# l represents the last timestep values, so in 1990's step, you have 1980 data being sourced.
```

```
# The begining of the main shell.
for y in 1990 2000 2010 2020 2030 2040 2050
  do

# Sets the age to the current timestep.
age.sh $y $l

# Recalculates the agegroups for each species within a cell for the current timestep.
age.group.sh $y

# Creates ignition events and burns to the township level.
burn.sh $y

### Species die if they are both old and in poor growing conditions, may cause
# cell death or just the species proportion within the cell, if less than 50% and no
# other species are dead.
death.sh $y

### If a cell has burned or died it is reset for species compostion (from regen.prop.sh),
# age, agegroup, volume, and the pdead.$y used for the calculation of cell proportion dead
regeneration.sh $y

# To calculate the ten percent reduction in volume for overmature species within a cell
MDIAj.group5.sh $y

# Applies the MDIAj.group values for the number of hectars within the township, and its
# proportion by species through all agegroups.
growth.sh $y $l

### Calculates the difference between the current and the past time steps volume by species
# for use in model analysis.
volume.change.sh $y $l

l=$y

done
```

```
#!/bin/sh
# Written by Isobel Booth begun May23, 1995.    [fwi.layers.sh]
# This is not run within the shell, it is run before.

### Using the average fwi summer months value to determine fire frequency classes
# for each decade of the scenario.

### Presently divided up at  <1000=Low (1)  >1000&<1500=Medium (2)  >=1500=High
(3)
# These division boundaries may be changed, to achieve the area burned-to-seasonal FWI ratio.

r.mapcalc "fwi.calc.1980=((fwi.1980.jun.giss+fwi.1980.jul.giss+fwi.1980.aug.giss)/3)"
r.mapcalc "fwi.Adj4sh.1980=if(fwi.calc.1980<1000,1,if(fwi.calc.1980>=1000 && \
fwi.calc.1980<1500,2,if(fwi.calc.1980>=1500 && fwi.calc.1980<4000,3,999)))"

r.mapcalc "fwi.calc.1990=((fwi.1990.jun.giss+fwi.1990.jul.giss+fwi.1990.aug.giss)/3)"
r.mapcalc "fwi.Adj4sh.1990=if(fwi.calc.1990<1000,1,if(fwi.calc.1990>=1000 && \
fwi.calc.1990<1500,2,if(fwi.calc.1990>=1500 && fwi.calc.1990<4000,3,999)))"

r.mapcalc "fwi.calc.2000=((fwi.2000.jun.giss+fwi.2000.jul.giss+fwi.2000.aug.giss)/3)"
r.mapcalc "fwi.Adj4sh.2000=if(fwi.calc.2000<1000,1,if(fwi.calc.2000>=1000 && \
fwi.calc.2000<1500,2,if(fwi.calc.2000>=1500 && fwi.calc.2000<4000,3,999)))"

r.mapcalc "fwi.calc.2010=((fwi.2010.jun.giss+fwi.2010.jul.giss+fwi.2010.aug.giss)/3)"
r.mapcalc "fwi.Adj4sh.2010=if(fwi.calc.2010<1000,1,if(fwi.calc.2010>=1000 && \
fwi.calc.2010<1500,2,if(fwi.calc.2010>=1500 && fwi.calc.2010<4000,3,999)))"

r.mapcalc "fwi.calc.2020=((fwi.2020.jun.giss+fwi.2020.jul.giss+fwi.2020.aug.giss)/3)"
r.mapcalc "fwi.Adj4sh.2020=if(fwi.calc.2020<1000,1,if(fwi.calc.2020>=1000 && \
fwi.calc.2020<1500,2,if(fwi.calc.2020>=1500 && fwi.calc.2020<4000,3,999)))"

r.mapcalc "fwi.calc.2030=((fwi.2030.jun.giss+fwi.2030.jul.giss+fwi.2030.aug.giss)/3)"
r.mapcalc "fwi.Adj4sh.2030=if(fwi.calc.2030<1000,1,if(fwi.calc.2030>=1000 && \
fwi.calc.2030<1500,2,if(fwi.calc.2030>=1500 && fwi.calc.2030<4000,3,999)))"

r.mapcalc "fwi.calc.2040=((fwi.2040.jun.giss+fwi.2040.jul.giss+fwi.2040.aug.giss)/3)"
r.mapcalc "fwi.Adj4sh.2040=if(fwi.calc.2040<1000,1,if(fwi.calc.2040>=1000 && \
fwi.calc.2040<1500,2,if(fwi.calc.2040>=1500 && fwi.calc.2040<4000,3,999)))"

r.mapcalc "fwi.calc.2050=((fwi.2050.jun.giss+fwi.2050.jul.giss+fwi.2050.aug.giss)/3)"
r.mapcalc "fwi.Adj4sh.2050=if(fwi.calc.2050<1000,1,if(fwi.calc.2050>=1000 && \
fwi.calc.2050<1500,2,if(fwi.calc.2050>=1500 && fwi.calc.2050<4000,3,999)))"

g.remove rast=fwi.calc.1980,fwi.calc.1990,fwi.calc.2000,fwi.calc.2010,fwi.calc.2020,\
fwi.calc.2030,fwi.calc.2040,fwi.calc.2050
```

```
#!/bin/sh
# Written by Isobel Booth  begun May 8, 1995.    [regen.prop.sh]
# This is run before the shell, not within it

### Calculates the proportional occupancy for each timestep by each species of a cell,
# based on the regression relationship developed with climate. The values are only
# used when a cell requires regeneration. The temperature is transformed
# back to degrees celsius, and the final multiplication by 10000 is to correct the units
# for the model (remembering GRASS does not hold decimals in raster maps).
for y in 1980 1990 2000 2010 2020 2030 2040 2050
 do
### Black Spruce proportions

r.mapcalc "bs.regen.$y=((11.43982730 + (0.017533773*(temp.$y.jan.giss*0.1 -273)) +\
(1.10967686*(temp.$y.may.giss*0.1 -273)) +(0.091287551*(temp.$y.jun.giss*0.1 -273))+\
(-0.51030352*(temp.$y.aug.giss*0.1 -273)) + (0.50502134*(temp.$y.sep.giss*0.1 -273)) +\
 (0.037669722*(temp.$y.oct.giss*0.1 -273)) +\
(-0.0026862120*precip.$y.apr.giss) + (-0.00065904614*precip.$y.jun.giss) + \
(0.0078655814*precip.$y.sep.giss) + (-0.0065316897*precip.$y.oct.giss)  + \
(0.028269124*ETp.$y.apr) + (-0.20027214*ETp.$y.may) +\ (0.11550856*ETp.$y.aug) +\
(0.021201257*ETp.$y.oct) + (-0.037949464*ETp.$y.ann))*10000)"

### White Spruce proportions

r.mapcalc "sp.regen.$y=((-1.684347465+ (0.0457164699*(temp.$y.jan.giss*0.1 -273)) +\
(0.0989195621*(temp.$y.may.giss*0.1 -273)) +\
(-0.250130554(temp.$y.aug.giss*0.1 -273))+(0.169224788*(temp.$y.sep.giss*0.1 -273)) +\
(-0.193215631*(temp.$y.oct.giss*0.1 -273)) + (-0.0246653225*precip.$y.jun.giss) +\
(-0.00998765922*precip.$y.sep.giss) + (0.00345528093*precip.$y.oct.giss) +\
(0.00682435445*precip.$y.totalsummer) +\
(0.0558317351*ETp.$y.aug) + (0.00929460841*ETp.$y.oct))*10000)"

### Lodgepole Pine proportions

r.mapcalc "pi.regen.$y=((7.912776962 + (-0.0367397389*(temp.$y.jan.giss*0.1 -273)) +\
(-0.0640391414*(temp.$y.jun.giss*0.1 -273)) + \
(0.410209108*(temp.$y.aug.giss*0.1 -273))+\
(0.197486193*(temp.$y.sep.giss*0.1 -273))+(0.245567381*(temp.$y.oct.giss*0.1 -273)) +\
(0.006895934054*precip.$y.apr.giss) + (0.0194099075*precip.$y.jun.giss) +
(0.00714102884*precip.$y.sep.giss) + (0.0132078599*precip.$y.oct.giss) +
(-0.00422645320*precip.$y.totalsummer) +\
(-0.0249773138*precip.$y.mean.annual) + (-0.0605581464*ETp.$y.may) + \
(-0.107699689*ETp.$y.aug))*10000)"

### Trembling Aspen proportions
```

```
r.mapcalc "tr.regen.$y=((-2.659277191 + (-0.0341932749*(temp.$y.jan.giss*0.1 -273)) +\
(-0.0541458365*(temp.$y.jun.giss*0.1 -273)) +\
(-0.114585832*(temp.$y.oct.giss*0.1 -273)) + (0.00836080627*precip.$y.apr.giss) +\
(-0.00860668391*precip.$y.sep.giss) +\
(-0.00749024290*precip.$y.oct.giss) + (0.0166649743*precip.$y.mean.annual) +\
(0.00683689305*ETp.$y.apr) + (0.0356063579*ETp.$y.may) +\
(0.0112027760*ETp.$y.aug) +\
(0.00787431032*ETp.$y.oct))*10000)"

### Paper Birch proportions

r.mapcalc "pb.regen.$y=((-0.1990750638+(-0.02592927624*(temp.$y.oct.giss*0.1-273))
+\
(0.001143678221*precip.$y.apr.giss) + (-0.002333500416*precip.$y.oct.giss) +\
(-0.0002921717267*precip.$y.totalsummer) + (0.004533873697*precip.$y.mean.annual) +\
(0.003708982991*ETp.$y.may) + (0.002119279989*ETp.$y.oct))*10000)"


### Summation and Division to get 100% occupancy for regeneration of cells
# to adjust for any over or under occupancy of cells.

r.mapcalc "sum.regen.$y = (bs.regen.$y + sp.regen.$y + pi.regen.$y + tr.regen.$y +
pb.regen.$y)"

r.mapcalc "bs.prop.regen.$y=((bs.regen.$y) / (sum.regen.$y)*10000)"
r.mapcalc "sp.prop.regen.$y=((sp.regen.$y) / (sum.regen.$y)*10000)"
r.mapcalc "pi.prop.regen.$y=((pi.regen.$y) / (sum.regen.$y)*10000)"
r.mapcalc "tr.prop.regen.$y=((tr.regen.$y) / (sum.regen.$y)*10000)"
r.mapcalc "pb.prop.regen.$y=((pb.regen.$y) / (sum.regen.$y)*10000)"

g.remove rast=bs.regen.$y,sp.regen.$y,pi.regen.$y,tr.regen.$y,pb.regen.$y,sum.regen.$y

done
```

```
#!/bin/sh
# Written by Isobel Booth begun May 5, 1995. [MDIAj.group.sh]
# updated May 24/95 and again May 29/95 3rd time Oct 24/95.
# This is run before the shell, not within it

### To calculate the increase in volume for Age Groups 1-4 and all species based
# on the regression equations developed in SAS. The temperature is transformed
# back to degrees celsius, and the final multiplication by 100 is to correct the units
# for the model (remembering GRASS does not hold decimals in raster maps).

for y in 1980 1990 2000 2010 2020 2030 2040 2050
 do
### Black Spruce MDI

r.mapcalc "BSpMDIAj.g1.$y=((8.933652285 + (0.837723224*(temp.$y.aug.giss*0.1 -273)) +\
(0.455995788*precip.$y.apr.giss) + (-0.0247125776*precip.$y.totalsummer))*100)"
r.mapcalc "BSpMDIAj.g1.$y=if(BSpMDIAj.g1.$y<0,0,BSpMDIAj.g1.$y)"

r.mapcalc "BSpMDIAj.g2.$y=((6.001300696 + (-0.357499100*precip.$y.sep.giss) +\
(0.662551775*precip.$y.mean.annual.giss) + (0.275865770*ETp.$y.apr) +\
(-0.468516915*ETp.$y.oct))*100)"
r.mapcalc "BSpMDIAj.g2.$y=if(BSpMDIAj.g2.$y<0,0,BSpMDIAj.g2.$y)"

r.mapcalc "BSpMDIAj.g3.$y=((255.0480676 + (0.7032465*(temp.$y.jan.giss*0.1 -273)) +\
(-6.1346701*(temp.$y.jun.giss*0.1 -273)) + (18.3096651*(temp.$y.aug.giss*0.1 -273)) +\
(-5.4459840*(temp.$y.sep.giss*0.1 -273)) + (-0.3612497*precip.$y.apr.giss) +\
(0.07936509*precip.$y.totalsummer) +(0.2771189*ETp.$y.apr) + \
(-4.6082135*ETp.$y.aug) + (-0.4918582*ETp.$y.oct))*100)"
r.mapcalc "BSpMDIAj.g3.$y=if(BSpMDIAj.g3.$y<0,0,BSpMDIAj.g3.$y)"

r.mapcalc "BSpMDIAj.g4.$y = (0)"

### White Spruce MDI

r.mapcalc "SpMDIAj.g1.$y=((-49.87079984 + (-1.62907866*(temp.$y.jan.giss*0.1 -273)) +\
(0.52632642*precip.$y.apr.giss) +(-0.59858599*precip.$y.sep.giss) +\
(1.20747657*precip.$y.mean.annual))*100)"
r.mapcalc "SpMDIAj.g1.$y=if(SpMDIAj.g1.$y<0,0,SpMDIAj.g1.$y)"

r.mapcalc "SpMDIAj.g2.$y=((-167.4196501 + (-0.8024511*(temp.$y.jan.giss*0.1 -273)) +\
(-19.8180388*(temp.$y.may.giss*0.1 -273)) + (-1.4954454*(temp.$y.jun.giss*0.1 -273)) +\
(8.5777031*(temp.$y.aug.giss*0.1 -273))+ (2.7061377*(temp.$y.sep.giss*0.1 -273)) +\
(-1.2253510*(temp.$y.oct.giss*0.1 -273))+ (-0.1028938*precip.$y.apr.giss) +\
(-0.4043351*precip.$y.sep.giss) +(-0.2305938*precip.$y.oct.giss) +\
(1.3105943*precip.$y.mean.annual) + (3.1594379*ETp.$y.may) + \
(-1.9090016*ETp.$y.aug) + (-0.7368680*ETp.$y.oct) + (0.4915950*ETp.$y.ann))*100)"

r.mapcalc "SpMDIAj.g2.$y=if(SpMDIAj.g2.$y<0,0,SpMDIAj.g2.$y)"
```

```
r.mapcalc "SpMDIAj.g3.$y=((-6.201869669+(0.747379153*(temp.$y.jan.giss*0.1-273))+\
(-2.053763395*(temp.$y.oct.giss*0.1 -273)) + (-0.233048593*precip.$y.sep.giss) +\
(-0.192167749*precip.$y.oct.giss) + (0.562423821*precip.$y.mean.annual) +\
(0.166453089*ETp.$y.apr) + (0.684212827*ETp.$y.may) +\
(-0.478672854*ETp.$y.oct))*100)"
r.mapcalc "SpMDIAj.g3.$y=if(SpMDIAj.g3.$y<0,0,SpMDIAj.g3.$y)"

r.mapcalc "SpMDIAj.g4.$y = (0)"

### Lodgepole Pine MDI

r.mapcalc "PiMDIAj.g1.$y=((-54.10266881+(-1.86841417*(temp.$y.jan.giss*0.1 -273))
+\
(0.89434451*precip.$y.totalsummer))*100)"
r.mapcalc "PiMDIAj.g1.$y=if(PiMDIAj.g1.$y<0,0,PiMDIAj.g1.$y)"

r.mapcalc "PiMDIAj.g2.$y=((9.386932579+(-1.531757905*(temp.$y.jan.giss*0.1 -273))
+\
(-5.423143492*(temp.$y.jun.giss*0.1 -273))+ (8.030356972*(temp.$y.sep.giss*0.1 -273))
+\
(-0.294666898*precip.$y.apr.giss) + (-0.289898159*precip.$y.sep.giss) +\
(0.771394601*precip.$y.mean.annual) +(0.478108682*ETp.$y.apr) +\
(-0.575329816*ETp.$y.may) + (-0.612468499*ETp.$y.oct))*100)"
r.mapcalc "PiMDIAj.g2.$y=if(PiMDIAj.g2.$y<0,0,PiMDIAj.g2.$y)"

r.mapcalc "PiMDIAj.g3.$y=((-8.618670278+(-0.659930125*(temp.$y.jan.giss*0.1
-273))+\
(-2.706399573*(temp.$y.may.giss*0.1 -273)) + \
(-2.4033608310*(temp.$y.jun.giss*0.1 -273)) +\
(5.582590220*(temp.$y.sep.giss*0.1 -273)) +(-3.146741048*(temp.$y.oct.giss*0.1 -273))
+\ (-0.404155115*precip.$y.jun.giss) +(-0.651445995*precip.$y.sep.giss) +\
(-0.240085969*precip.$y.oct.giss) +(0.129033795*precip.$y.mean.annual) +\
(1.250733486*precip.$y.mean.annual) + (0.574783703*ETp.$y.apr) +\
(-0.338535289*ETp.$y.oct)*100)"
r.mapcalc "PiMDIAj.g3.$y=if(PiMDIAj.g3.$y<0,0,PiMDIAj.g3.$y)"

r.mapcalc "PiMDIAj.g4.$y = (0)"

### Trembling Aspen MDI

r.mapcalc "TrMDIAj.g1.$y=((-0.0005793771 + (0.6091570094*precip.$y.oct.giss))*100)"
r.mapcalc "TrMDIAj.g1.$y=if(TrMDIAj.g1.$y<0,0,TrMDIAj.g1.$y)"

r.mapcalc "TrMDIAj.g2.$y=((-223.5283964+(-0.3137668*(temp.$y.jan.giss*0.1 -273)) +\
(1.7912406*(temp.$y.may.giss*0.1 -273)) + (2.4290324*(temp.$y.jun.giss*0.1 -273)) +\
```

```
(-19.9012739*(temp.$y.aug.giss*0.1 -273)) +(9.4834100*(temp.$y.sep.giss*0.1 -273)) +\
(0.04669654*precip.$y.sep.giss) +(0.07273100*precip.$y.oct.giss) +\
(4.7195604*ETp.$y.aug) + (-0.3028311*ETp.$y.oct))*100)"
r.mapcalc "TrMDIAj.g2.$y=if(TrMDIAj.g2.$y<0,0,TrMDIAj.g2.$y)"

r.mapcalc "TrMDIAj.g3.$y=((0.185213169+(0.510107986*(temp.$y.aug.giss*0.1-273))+\
(4.998227931*(temp.$y.sep.giss*0.1 -273))+ (-4.425585286*(temp.$y.oct.giss*0.1-273))+\
(-0.524642831*precip.$y.apr.giss)+(0.497167832*precip.$y.mean.annual) +\
(0.451198157*ETp.$y.apr) + (-0.761532066*ETp.$y.may))*100)"
r.mapcalc "TrMDIAj.g3.$y=if(TrMDIAj.g3.$y<0,0,TrMDIAj.g3.$y)"

### Paper Birch MDI

r.mapcalc "PBMDIAj.g1.$y=((-241.9865032 + (-0.9965459*precip.$y.jun) +
(5.6878562*ETp.$y.may))*100)"
r.mapcalc "PBMDIAj.g1.$y=if(PBMDIAj.g1.$y<0,0,PBMDIAj.g1.$y)"

r.mapcalc "PBMDIAj.g2.$y=((20.48495284+(-1.74579473*(temp.$y.jun.giss*0.1-273)) +\
(1.91452706*(temp.$y.sep.giss*0.1 -273)) + (7.13043330*(temp.$y.oct.giss*0.1 -273)) +\
(-0.52657625*(precip.$y.apr.giss)) + (-0.11349929*(precip.$y.jun.giss)) +\
(0.54628858*precip.$y.mean.annual) +(-1.3539448*ETp.$y.oct))*100)"
r.mapcalc "PBMDIAj.g2.$y=if(PBMDIAj.g2.$y<0,0,PBMDIAj.g2.$y)"

r.mapcalc "PBMDIAj.g3.$y=((19.59111411+(-0.56918917*(temp.$y.jan.giss*0.1-273)) +\
(-2.85265510*(temp.$y.may.giss*0.1 -273)) +(5.80328606*(temp.$y.oct.giss*0.1 -273)) +\
(-0.44507693*precip.$y.apr.giss) +\
(-0.66192409*precip.$y.jun.giss) + (-0.18628619*precip.$y.sep.giss) +\
(0.61780927*precip.$y.mean.annual) +(0.41823122*ETp.$y.apr)+\
(-0.96217542*ETp.$y.oct))*100)"
r.mapcalc "PBMDIAj.g3.$y=if(PBMDIAj.g3.$y<0,0,PBMDIAj.g3.$y)"

 done
```

```
#!/bin/sh
# Written by Isobel Booth  begun May 9, 1995.   [age.sh]

## Sets the age to that of the current timestep by adding 10 years
# (1000 time units, remember no decimals)

r.mapcalc "age.$1 = (age.$2 + 1000) "
```

```
#!/bin/sh
# Written by Isobel Booth  begun May 8, 1995.  [age.group.sh]

### Species Age Group evaluation applied for each timestep in the model
# This could be reduced to just coniferous and deciduous agegroups only,
# but it has been kept for flexibility.

r.mapcalc "BSAgeg.$1 = if (age.$1 <= 5000, 1, if ( age.$1 > 5000 && age.$1 <= 12000, 2,\
 if( age.$1 > 12000 && age.$1 <= 20000,3, if(age.$1 > 20000 && age.$1 <= 23000,4,\
if(age.$1 > 23000 && age.$1 <= 25000, 5,6)))))"

r.mapcalc "SpAgeg.$1 = if (age.$1 <= 5000, 1, if ( age.$1 > 5000 && age.$1 <= 12000, 2,\
 if( age.$1 > 12000 && age.$1 <= 20000,3, if(age.$1 > 20000 && age.$1 <= 23000,4,\
if(age.$1 > 23000 && age.$1 <= 25000, 5,6)))))"

r.mapcalc "PiAgeg.$1 = if (age.$1 <= 4000, 1, if ( age.$1 > 4000 && age.$1 <= 8000, 2,\
 if( age.$1 > 8000 && age.$1 <= 12000, 3, if(age.$1 > 12000 && age.$1 <= 15000,4,\
if(age.$1 > 15000, 6,6)))))"

r.mapcalc "TrAgeg.$1 = if (age.$1 <= 3000, 1, if ( age.$1 > 3000 && age.$1 <= 7000, 2,\
 if( age.$1 > 7000 && age.$1 <= 8000, 3, if(age.$1 > 8000 && age.$1 <= 12000,5,\
if(age.$1 > 12000, 6,6)))))"

r.mapcalc "PBAgeg.$1 = if (age.$1 <= 3000, 1, if ( age.$1 > 3000 && age.$1 <= 7000, 2,\
 if( age.$1 > 7000 && age.$1 <= 8000, 3, if(age.$1 > 8000 && age.$1 <= 12000,5,\
if(age.$1 > 12000, 6,6)))))"
```

```
#!/bin/sh
# Written by Isobel Booth begun May17, 1995. [burn.sh]

### The MBFP model calibration adjustments for GCM scenarios occur with the 'nsites'
# values, in total of %, and in their proportion to each fire level. This section creates the
# potential burn sites for the FWI categories.
r.random input=flat raster=random.fire1 nsites=0.01%
r.random input=flat raster=random.fire2 nsites=0.03%
r.random input=flat raster=random.fire3 nsites=0.09%

### Flags (given value of 1) for the ignition events that are within their FWI category
r.mapcalc "burnsites = if (random.fire1==1 && fwi.Adj4sh.$1==1,1, if (random.fire2==1 && \
fwi.Adj4sh.$1==2,1,if (random.fire3==1 && fwi.Adj4sh.$1==3,1,0)))"

### Burn sites gain township labels
r.mapcalc "township.ignitions=(townships*burnsites)"

r.stats -1z input=township.ignitions output=township.ignition.sites

### Township labels of burnsites selected lead (through the inference engine) to the
# burning of their entire township. The limit of 100 sites for inference is a limitation
# of the r.infer subshell, and causes the area able to be modelled to be limited in turn. Solutions
# to this limit are being pursued.

sort +0 -1 -u township.ignition.sites >tmp.townburn

echo "IFMAP townships" `awk '{printf "%s ", $1}' tmp.townburn `>interm
echo "THENMAPHYP 9 burned $1 township">>interm

r.infer file=interm

g.rename rast=infer,burned.townships.$1

### Burned townships are labeled with a value of 9 in the maplayer burned.townships.$1,
# and they will be recolonized in regeneration.sh
```

```
#!/bin/sh
# Written by Isobel Booth  begun May 8, 1995.    [death.sh]
# updated May 24/95
#The death part of the scenario, caused by age and poor climate conditions

### Calculating the proportion of cell that is dead (species that are old (Age Group 3
# or greater) and growth is poor at Age Group 3)

r.mapcalc "pdead.$1=if (BSAgeg.$1 >= 3 && BSpMDIAj.g3.$1 < 600, bsprop.$1, 0) +\
if (SpAgeg.$1 >= 3 && SpMDIAj.g3.$1 < 600, spprop.$1, 0) +\
if (PiAgeg.$1 >= 3 && PiMDIAj.g3.$1 < 600, piprop.$1, 0) +\
if (TrAgeg.$1 >= 3 && TrMDIAj.g3.$1 < 500, trprop.$1, 0) +\
if (PBAgeg.$1 >= 3 && PBMDIAj.g3.$1 < 500, pbprop.$1, 0)"

### To calculate the total portion of the cell that has accumulated as dead at
# the current timestep without regeneration. This means that the individual layers
# of pdead aren't true timestep layers, as they are reset to zero after regeneration.

r.mapcalc "sum.dead.$1=(pdead.1980+pdead.1990+pdead.2000+pdead.2010+pdead.2020+\
pdead.2030+pdead.2040+pdead.2050)"

### Creating a variable which will not be changed/reset within the shell
# and will hold the amount of cell death that occured in each timestep

r.mapcalc "prop.dead.$1=pdead.$1"

### To remove species considered dead from the growth scenario by changing
# their proportion value to zero, as they were old and poorly growing, but may
# not have caused their cell to die yet by proportion occupied as dead

r.mapcalc "bsprop.$1=if(BSAgeg.$1 >=3 && BSpMDIAj.g3.$1 < 600, 0, bsprop.$1)"
r.mapcalc "spprop.$1=if(SpAgeg.$1 >=3 && SpMDIAj.g3.$1 < 600, 0, spprop.$1)"
r.mapcalc "piprop.$1=if(PiAgeg.$1 >=3 && PiMDIAj.g3.$1 < 600, 0, piprop.$1)"
r.mapcalc "trprop.$1=if(TrAgeg.$1 >=3 && TrMDIAj.g3.$1 < 500, 0, trprop.$1)"
r.mapcalc "pbprop.$1=if(PBAgeg.$1 >=3 && PBMDIAj.g3.$1 < 500, 0, pbprop.$1)"

# Ideally I would have managed to get the standing volume of the
# dead species to decay rather than have it just not grow.

### Dead townships are labeled with a value equal to or greater than 5000 (50%, without
# decimals ...GRASS) in sum.dead.$1. They will be recolonized in regeneration.sh
```

```
#!/bin/sh
# Written by Isobel Booth  begun May 8, 19,9,5.  [establishment.sh].

### The resetting of age, proportions, and volume for each species after township fire or death.
# death of a cell occurs when 50% or more is killed in the death shell, and added to sum.dead

### Age itself
r.mapcalc "age.$1 = if (sum.dead.$1 > 5000 || burned.townships.$1=9, 500, age.$1)"

### Age groups
# (where the timesteps current age group will replace itself unless burn or death of the township)

r.mapcalc "BSAgeg.$1 = if (sum.dead.$1 > 5000 || burned.townships.$1==9, 1, BSAgeg.$1)"
r.mapcalc "SpAgeg.$1 = if (sum.dead.$1 > 5000 || burned.townships.$1==9, 1, SpAgeg.$1)"
r.mapcalc "PiAgeg.$1 = if (sum.dead.$1 > 5000 || burned.townships.$1==9, 1, PiAgeg.$1)"
r.mapcalc "TrAgeg.$1 = if (sum.dead.$1 > 5000 || burned.townships.$1==9, 1, TrAgeg.$1)"
r.mapcalc "PBAgeg.$1 = if (sum.dead.$1 > 5000 || burned.townships.$1==9, 1, PBAgeg.$1)"

### Proportions
# if die or burn the proprotions are replaced with that of sp's.prop.regen.$1 from regen.prop.sh

r.mapcalc "bsprop.$1 = if (sum.dead.$1 > 5000 || burned.townships.$1==9, bs.prop.regen.$1,\
bsprop.$1)"
r.mapcalc "spprop.$1 = if (sum.dead.$1 > 5000 || burned.townships.$1==9, sp.prop.regen.$1,\
spprop.$1)"
r.mapcalc "piprop.$1 = if (sum.dead.$1 > 5000 || burned.townships.$1==9, pi.prop.regen.$1,\
piprop.$1)"
r.mapcalc "trprop.$1 = if (sum.dead.$1 > 5000 || burned.townships.$1==9, tr.prop.regen.$1,\
trprop.$1)"
r.mapcalc "pbprop.$1 = if (sum.dead.$1 > 5000 || burned.townships.$1==9, pb.prop.regen.$1,\
pbprop.$1)"

### Volumes
# if burn or die, the volumes go to zero (done before the growth addition for the current timestep)
r.mapcalc "bsvol.$1 = if (sum.dead.$1 > 5000 || burned.townships.$1==9, 0, bsvol.$1)"
r.mapcalc "spvol.$1 = if (sum.dead.$1 > 5000 || burned.townships.$1==9, 0, spvol.$1)"
r.mapcalc "pivol.$1 = if (sum.dead.$1 > 5000 || burned.townships.$1==9, 0, pivol.$1)"
r.mapcalc "trvol.$1 = if (sum.dead.$1 > 5000 || burned.townships.$1==9, 0, trvol.$1)"
r.mapcalc "pbvol.$1 = if (sum.dead.$1 > 5000 || burned.townships.$1==9, 0, pbvol.$1)"

### Resetting the sum.dead's
# as post cell death they are returned to zero, otherwise their additive values would
# cause the cell sum sum.dead.for the next timestep to have a value other than zero
# which it can't as the age is still in Agegroup 1 for all species.
r.mapcalc "sum.dead.1980 = if(sum.dead.$1 > 5000 || burned.townships.$1==9, 0,\
sum.dead.1980)"
r.mapcalc "sum.dead.1990 = if(sum.dead.$1 > 5000 || burned.townships.$1==9, 0,\
sum.dead.1990)"
r.mapcalc "sum.dead.2000 = if(sum.dead.$1 > 5000 || burned.townships.$1==9, 0,\
```

```
sum.dead.2000)"
r.mapcalc "sum.dead.2010 = if(sum.dead.$1 > 5000 || burned.townships.$1==9, 0,\
sum.dead.2010)"
r.mapcalc "sum.dead.2020 = if(sum.dead.$1 > 5000 || burned.townships.$1==9, 0,\
sum.dead.2020)"
r.mapcalc "sum.dead.2030 = if(sum.dead.$1 > 5000 || burned.townships.$1==9, 0,\
sum.dead.2030)"
r.mapcalc "sum.dead.2040 = if(sum.dead.$1 > 5000 || burned.townships.$1==9, 0,\
sum.dead.2040)"
r.mapcalc "sum.dead.2050 = if(sum.dead.$1 > 5000 || burned.townships.$1==9, 0,\
sum.dead.2050)"
```

```
#!/bin/sh
# Written by Isobel Booth begun May 23, 1995. [MDIAj.group5.sh]

### To calculate the decrease in volume for species in Age Group 5 based on a 10% decay rate.

### Black Spruce MDI
r.mapcalc "BSpMDIAj.g5.$1 = (bsvol.$1 * (-0.1))"

### White Spruce MDI
r.mapcalc "SpMDIAj.g5.$1 = (spvol.$1 * -(0.1))"

### Lodgepole Pine MDI
# No decay period was assigned to this species.

### Trembling Aspen MDI
r.mapcalc "TrMDIAj.g5.$1 = (trvol.$1 * -(0.1))"

### Paper Birch MDI
r.mapcalc "PBMDIAj.g5.$1 = (pbvol.$1 * -(0.1))"
```

```
#!/bin/sh
# Written by Isobel Booth begun May 9, 1995. [growth.sh]

r.mapcalc "bsvol.$1 =\
if (BSAgeg.$1==1, eval (bsvol.$2 + (BSpMDIAj.g1.$1 * 0.01 * sfvha * bsprop.$1 * 0.0001)), \
if (BSAgeg.$1==2, eval (bsvol.$2 + (BSpMDIAj.g2.$1 * 0.01 * sfvha * bsprop.$1 * 0.0001)), \
if (BSAgeg.$1==3, eval (bsvol.$2 + (BSpMDIAj.g3.$1 * 0.01 * sfvha * bsprop.$1 * 0.0001)), \
if (BSAgeg.$1==4, eval (bsvol.$2 + (BSpMDIAj.g4.$1 * 0.01 * sfvha * bsprop.$1 * 0.0001)), \
if (BSAgeg.$1==5, eval (bsvol.$2 + (BSpMDIAj.g5.$1)), \
if (BSAgeg.$1==6, eval (bsvol.$2 - bsvol.$2), -11111111))))))"

r.mapcalc "spvol.$1 =\
if (SpAgeg.$1==1, eval (spvol.$2 + (SpMDIAj.g1.$1 * 0.01 * sfvha * spprop.$1 * 0.0001)), \
if (SpAgeg.$1==2, eval (spvol.$2 + (SpMDIAj.g2.$1 * 0.01 * sfvha * spprop.$1 * 0.0001)), \
if (SpAgeg.$1==3, eval (spvol.$2 + (SpMDIAj.g3.$1 * 0.01 * sfvha * spprop.$1 * 0.0001)), \
if (SpAgeg.$1==4, eval (spvol.$2 + (SpMDIAj.g4.$1 * 0.01 * sfvha * spprop.$1 * 0.0001)), \
if (SpAgeg.$1==5, eval (spvol.$2 + (SpMDIAj.g5.$1)), \
if (SpAgeg.$1==6, eval (spvol.$2 - spvol.$2), -22222222))))))"

r.mapcalc "pivol.$1 =\
if (PiAgeg.$1==1, eval (pivol.$2 + (PiMDIAj.g1.$1 * 0.01 * sfvha * piprop.$1 * 0.0001)), \
if (PiAgeg.$1==2, eval (pivol.$2 + (PiMDIAj.g2.$1 * 0.01 * sfvha * piprop.$1 * 0.0001)), \
if (PiAgeg.$1==3, eval (pivol.$2 + (PiMDIAj.g3.$1 * 0.01 * sfvha * piprop.$1 * 0.0001)), \
if (PiAgeg.$1==4, eval (pivol.$2 + (PiMDIAj.g4.$1 * 0.01 * sfvha * piprop.$1 * 0.0001)), \
if (PiAgeg.$1==6, eval (pivol.$2 - pivol.$2), -33333333))))))"

r.mapcalc "trvol.$1 =\
if (TrAgeg.$1==1, eval (trvol.$2 + (TrMDIAj.g1.$1 * 0.01 * sfvha * trprop.$1 * 0.0001)), \
if (TrAgeg.$1==2, eval (trvol.$2 + (TrMDIAj.g2.$1 * 0.01 * sfvha * trprop.$1 * 0.0001)), \
if (TrAgeg.$1==3, eval (trvol.$2 + (TrMDIAj.g3.$1 * 0.01 * sfvha * trprop.$1 * 0.0001)), \
if (TrAgeg.$1==5, eval (trvol.$2 + (TrMDIAj.g5.$1)), \
if (TrAgeg.$1==6, eval (trvol.$2 - trvol.$2), -44444444)))))"

r.mapcalc "pbvol.$1 =\
if (PBAgeg.$1==1, eval (pbvol.$2 + (PBMDIAj.g1.$1 * 0.01 * sfvha * pbprop.$1 * 0.0001)), \
if (PBAgeg.$1==2, eval (pbvol.$2 + (PBMDIAj.g2.$1 * 0.01 * sfvha * pbprop.$1 * 0.0001)), \
if (PBAgeg.$1==3, eval (pbvol.$2 + (PBMDIAj.g3.$1 * 0.01 * sfvha * pbprop.$1 * 0.0001)), \
if (PBAgeg.$1==5, eval (pbvol.$2 + (PBMDIAj.g5.$1)), \
if (PBAgeg.$1==6, eval (pbvol.$2 - pbvol.$2), -55555555)))))"

### Value conversion is necessary, as decimals are not supported in GRASS.
# sfvha are in true numbers of hectares, as is volume in true numbers of m
# MDIAj's have 100 units for every 1m³/ha
# prop have 100 units for every 0.01 proportion (also known as 1%), and desire
# the proportions to add to 1 (100%)
# Therefore each are converted to produce volume in 'true' units.
```

```
### Species death caused by volume decreasing to zero in growth shell
# so then assess species proportions alive within the unit, and reassign values if unit has died.
r.mapcalc "sumdead.2.$1=if(bsvol.$1<=0 && bsprop.$1>0 && age.$1 != 500, bsprop.$1, 0)+\
if(spvol.$1<=0 && spprop.$1>0 && age.$1 != 500, spprop.$1, 0)+\
if(pivol.$1<=0 && piprop.$1>0 && age.$1 != 500, piprop.$1, 0)+\
if(trvol.$1<=0 && trprop.$1>0 && age.$1 != 500, trprop.$1, 0)+\
if(pbvol.$1<=0 && pbprop.$1>0 && age.$1 != 500, pbprop.$1, 0) + sum.dead.$1"

### With species dead due to volume reduction, the unit is tested for unit death again
# (to see if dead proportion is now bumped up to be greater than 50% from that of death.sh).
r.mapcalc "toast.$1= if(sum.dead.$1 <=5000 && sumdead.2.$1 >5000,1,0)"
# The unit would show a value of 1 in toast.$1 if the unit does die due to volume reduction in
# time-step $1.

### Re-assigning the species values if death to the unit did occur due to volume reduction.
r.mapcalc "age.$1 = if (toast.$1==1,500,age.$1)"
r.mapcalc "BSAgeg.$1 = if (toast==1, 1, BSAgeg.$1)"
r.mapcalc "SpAgeg.$1 = if (toast==1, 1, SpAgeg.$1)"
r.mapcalc "PiAgeg.$1 = if (toast==1, 1, PiAgeg.$1)"
r.mapcalc "TrAgeg.$1 = if (toast==1, 1, TrAgeg.$1)"
r.mapcalc "PBAgeg.$1 = if (toast==1, 1, PBAgeg.$1)"
r.mapcalc "bsprop.$1 = if(toast==1, bs.prop.regen.$1,\ bsprop.$1)"
r.mapcalc "spprop.$1 = if (toast==1, sp.prop.regen.$1,\ spprop.$1)"
r.mapcalc "piprop.$1 = if (toast==1, pi.prop.regen.$1,\ piprop.$1)"
r.mapcalc "trprop.$1 = if (toast==1, tr.prop.regen.$1,\ trprop.$1)"
r.mapcalc "pbprop.$1 = if (toast==1, pb.prop.regen.$1,\ pbprop.$1)"
r.mapcalc "bsvol.$1 = if (toast==1, eval(BSpMDIAj.g1.$1 * 0.01 * sfvha * bsprop.$1 * 0.0001),
bsvol.$1)"
r.mapcalc "spvol.$1 = if (toast==1, eval(SpMDIAj.g1.$1 * 0.01 * sfvha * spprop.$1 * 0.0001),
spvol.$1)"
r.mapcalc "pivol.$1 = if (toast==1, eval(PiMDIAj.g1.$1 * 0.01 * sfvha * piprop.$1 * 0.0001),
pivol.$1)"
r.mapcalc "trvol.$1 = if (toast==1, eval(TrMDIAj.g1.$1 * 0.01 * sfvha * trprop.$1 * 0.0001),
trvol.$1)"
r.mapcalc "pbvol.$1 = if (toast==1, eval(PBMDIAj.g1.$1 * 0.01 * sfvha * pbprop.$1 * 0.0001),
pbvol.$1)"
```

```
#!/bin/sh
# Written by Isobel Booth begun May 29, 1995.    [volume.change.sh]

# To calculate each timesteps net difference in species volume for model analysis.

r.mapcalc "bsvol.change.$1=(bsvol.$y-bsvol.$2)"
r.mapcalc "spvol.change.$1=(spvol.$y-spvol.$2)"
r.mapcalc "pivol.change.$1=(pivol.$y-pivol.$2)"
r.mapcalc "trvol.change.$1=(trvol.$y-trvol.$2)"
r.mapcalc "pbvol.change.$1=(pbvol.$y-pbvol.$2)"
```