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Modeling Boreal Forest Response to Climate Variability In Central Canada

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For the Degree of

MASTER OF SCIENCE

Department of Geography
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ABSTRACT

This study examines the importance of short-term climate variability when simulating forest succession using ecological process models. A version of the FORSKA2 forest gap model was modified for use with daily climate data and applied along a transect of sites crossing the boreal region in central Canada, including the aspen-parkland and forest-tundra ecotones where impacts of climatic change on forest ecosystems could be particularly significant. The model's sensitivity to forcing with daily climate observations compared to monthly mean and long term averages of monthly mean climate data was investigated. Inclusion of daily climate (minimum and maximum temperature and total precipitation) improved the simulations of key characteristics of present-day forest along the transect, and was particularly important at the ecotones. The results demonstrate that changes in variability associated with future change in mean climate are likely to be important when trying to predict boreal forest responses to projected future climate change. Ideally, the use of projected daily climate data or data based on the statistical characteristics of daily climate is highly recommended for future impact studies. A number of approaches to further improve the functioning of the model are also presented.

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1 INTRODUCTION

The composition and geographic distribution of the forests of North America have continuously changed in response to shifts in climate in the past (Ritchie, 1987; Foley *et al.*, 1994; Bigelow, 2003; Kaplan, 2003; Gajewski and MacDonald, 2004). While results vary, many ecosystem models predict significant changes for the boreal forest in response to anthropogenic climate change of the magnitude projected by the Intergovernmental Panel on Climate Change (IPCC, 2007b), and associated factors such as a change in the frequency of forest fires (Flannigan *et al.*, 2008). Potential responses of this biome include widespread poleward displacement of the treeline (Kittel *et al.*, 2000; Kaplan, 2003; ACIA, 2004; Callaghan, 2004; Soja *et al.*, 2007), a northward expansion of grassland at the southern forest-prairie limit (Hogg and Hurdle, 1995), and regional and local changes in productivity and species composition (Botkin and Nisbet, 1992; Lindner *et al.*, 1996; Price and Apps, 1996; Bugmann and Pfister, 2000; Price *et al.*, 2005). However, predictions of future climate change impacts on the boreal forest are difficult because of the many uncertainties that remain in projections of future climate change (Fischlin *et al.*, 1995; IPCC, 2007b) and the complex response of ecosystems at different temporal and spatial scales (Hare and Ritchie, 1972; Pearson and Dawson, 2003; NRTEE, 2005).

In particular, broad-scale climatic influences can be modified by factors such as climate variability and extremes that impact forest dynamics particularly at the regional and local levels (Larsen, 1980; Woodward, 1987; Bonan and Shugart, 1989; Gajewski and MacDonald, 2004). Changes in climate variability and extreme events associated with a general warming trend may therefore be important factors controlling future changes in the boreal ecosystem (Lindner *et al.*, 1996; Price and Apps, 1996; Price *et al.*, 1999a; Bugmann and Pfister, 2000; Price *et al.*, 2005). It is increasingly recognized that climate change impact assessment needs to take these factors into account (IPCC, 2007a).

Forest gap models are a class of ecological process model that simulate the behavior of forests in response to small-scale processes and spatial dynamics (Botkin *et al.*, 1972a; Larsen, 1980; Shugart, 1984). They are therefore well suited to investigating species and community-level response to climate variability (Botkin and Nisbet, 1992; Waring and Running, 1998; Bugmann and Pfister, 2000; Nalder, 2002; Pearson and Dawson, 2003). Nonetheless, only a small number of studies have examined the influence of climate variability in present-day forest composition (Lindner *et al.*, 1996; Price *et al.*, 1999a) and only one the possible impact of future changes in (monthly mean) climate variability (Bugmann and Pfister, 2000). The significance of climate variability to forest dynamics has not been adequately considered in gap model studies and further research is needed.

This study proposes that boreal forest species composition and tree growth is sensitive to short-term variability in temperature and precipitation and, as a consequence, the predictive capabilities of gap models will improve with use of higher resolution climate data. To test the hypothesis, the study investigates the effects of the use of different resolution climate data (daily observations versus monthly mean and constant climate) on a gap model's simulation of boreal forest structure and species composition and growth along a north-south climate gradient in central Canada, including the southern and northern ecotone where ecosystem sensitivity to climate variability is expected to be particularly important. The FORSKA-2V patch model, a widely-tested model with a demonstrated ability to reproduce some key characteristics of boreal forests reasonably well in central Canada, is used as the basis for the study (Prentice *et al.*, 1993; Price and Apps, 1996; Price *et al.*, 1999a; Bugmann *et al.*, 2001). Simulation results are evaluated on the basis of whether forcing the model with daily climate data improves the accuracy of the model's predictions (e.g. the ability to reproduce observed present-day species composition and growth) and/or its generality (e.g. the ability to perform well over more bioclimatic zones). Improved accuracy will indicate the importance of considering changes in daily climate variability when assessing the potential impacts of future climate change on the boreal forest. Improved generality will suggest that the representation of daily climate variability enhances the model's suitability for simulating ecosystem responses to a range of possible future climate changes (Shugart, 1984). The study is intended to contribute to a better understanding of the relationship between boreal forest dynamics and climate variability and provide important information for assessing the impacts of climate change on the boreal forest.

Specifically, the study will:

- Modify the FORSKA-2V model to work with daily climate input data.
- Examine how forcing the model with daily climate impacts the simulated environment compared to monthly mean and constant climate.
- Evaluate the effects of different resolution climate input data (daily, monthly mean and constant climate) on the model's ability to reproduce present-day patterns in boreal forest structure at sites along a transect of bioclimatic zones, and species composition and growth at each of the selected sites.
- Assess the strengths and limitations of the model and how the latter may be resolved.
- Discuss the implications of the findings for the study of boreal forest ecosystem sensitivity to the impacts of climate change, and for the future use of the FORSKA-2V forest patch model.

For the purpose of this study, the following terms will be used (Table 1).

Table 1. List of terms and their definition as used in this study.

Term	Definition
Climate	the statistical description of the mean and variability of meteorological observations over a period of at least 30-years
Climate change	statistically significant changes in the mean climate or its variability over extended periods
Climate variability	variations around the mean climate, such as standard deviations, extreme events, etc.
Constant climate	the long-term average of monthly mean climate variables, i.e. with no inter-annual variability
Current climate	observed, historical climate records
Daily climate	observed daily climate records
Future climate	model projections or plausible assumptions about the state of the future climate
Monthly mean climate	multi-year records of monthly mean climate variables, i.e. with inter-annual variability

2 LITERATURE REVIEW

2.1 Forests, Climate & Climate Change

The locations of the transitions between the Canadian boreal forest and adjacent vegetation zones (ecotones) are highly correlated with climatic factors (Larsen, 1980; Woodward, 1987; Hogg, 1994; Elliot-Fisk, 2000). Temperature is a main limiting factor, particularly the cold winters and short, cool summers at the northern boundary (Hare and Ritchie, 1972; Larsen, 1980; Oechel and Lawrence, 1985). Moisture gradients are important, particularly in the southwest (Larsen, 1980; Bonan and Shugart, 1989; Hogg, 1994; Hogg and Hurdle, 1995) where the southern boreal meets the Canadian prairies and forms the aspen parkland transition zone. The distribution of individual taxa also correlates well with average climate, especially temperature, at the continental to global scale. However, there is less correspondence at smaller scales (Pearson and Dawson, 2003; Gajewski and MacDonald, 2004; Soja *et al.*, 2007). The mosaic of forest types found across the boreal forest suggest that limiting factors can be regional and site-specific (Bonan and Shugart, 1989; Nalder, 2002) and that climatic variability and extremes may have a greater impact on species distribution and abundance than average climate (Larsen, 1980; Woodward, 1987; Bonan and Shugart, 1989; Timoney *et al.*, 1992; Bonan and Sirois, 1992; Price and Apps, 1996; Waring and Running, 1998; Natural Resources Canada, 2002).

Extreme climatic events and/or rapid change can affect forests and damage individual trees in many ways. The largest influence on boreal forest structure is arguably stand-replacing wildfire activity. Prolonged, high temperatures and the timing of seasonal precipitation can increase the risk of forest fires (Baxter, 1995; Flannigan *et al.*, 2008). Unseasonably high or low temperatures and precipitation can affect seed production and dispersal, seedling establishment, and flowering. Extremes can cause cessation of growth and even death of mature trees (Larsen, 1980; Oechel and Lawrence, 1985; Kimmins, 2004). Unseasonably high winter or spring temperatures can affect chilling requirements, the breaking of dormancy, and increase the risk of frost damage (Colombo, 1998;

McCarthy, 2001; Hogg *et al.*, 2002). At ecotones where species may be at the limit of their ecological tolerances, trees may be most sensitive to the occurrence of extreme events or variability (Botkin and Nisbet, 1992; Elliot-Fisk, 2000; IPCC, 2007a).

In Canada, a comprehensive nation-wide climate change impacts assessment concluded that the impacts on the Canadian boreal forest will have both positive and negative effects (Lemmen *et al.*, 2008). However, further understanding of how future changes in climate and climate variability may directly and indirectly alter species composition and growth and forest carbon storage is needed for more detailed assessment of ecosystem sensitivity and related economic vulnerabilities locally and nationally (Natural Resources Canada, 2005).

2.2 Forest Ecosystem Models

Ecological process models are one important tool to study past and present ecosystem dynamics and are a key source of information about possible future change. However, models designed to represent ecosystem dynamics at large spatial scales are not practical for examining the effects of climate variability and extremes and other factors such as disturbances, light resources, soil properties, inter-specific competition, habitat fragmentation, and topography, as the effect of many of these tend to be realized at smaller scales (Fischlin *et al.*, 1995; Pearson and Dawson, 2003; Soja *et al.*, 2007). On the other hand, forest gap models, also referred to as patch models, simulate forest succession on a number of small, separate patches of typically 0.1 hectare (ha) in area or less. Patch models simulate species composition and forest structure through simplified processes that represent individual tree establishment, growth and death in response to a variety of energy and water balance conditions on each patch (Botkin *et al.*, 1972a; Shugart, 1984; Leemans and Prentice, 1989; Prentice *et al.*, 1993; Bugmann and et al, 1996). Disturbances and competition among individuals for light and other resources are also considered. Site-specific environmental conditions influence the development of individual simulated trees, which in turn modify the environment (specifically in terms of light reaching the ground and soil water availability). The landscape-scale responses are depicted as the average results from an array of patches, each subjected to some randomized perturbations to ensure a range of plausible successional trajectories is simulated.

Patch models are therefore well suited to study species and community-level response to climate variability and the other site-specific factors (Larsen, 1980; Botkin and Nisbet, 1992; Price *et al.*, 1999a; Bugmann and Pfister, 2000; Nalder, 2002; Pearson and Dawson, 2003). However, only a limited number of studies have considered the role of climate variability in shaping current boreal forest dynamics. Lindner (1996) used FORSKA2 to assess the influence of historical daily and monthly mean climatic variations on forest dynamics in central Europe and Price *et al.* (1999) considered the impact of variable monthly mean versus constant climate on boreal forest in central Canada. Both researchers concluded that inclusion of climate variability improved the realism of simulated forest composition compared to simulations using constant climate.

Gap models have also been widely used to study forest response to potential future climate change. Nonetheless, almost all studies have examined responses to changes in mean temperature and total precipitation only (Botkin and Nisbet, 1992; Mearns *et al.*, 1992; Fischlin *et al.*, 1995; Price and Apps, 1996; Bugmann *et al.*, 2001; Smith *et al.*, 2001). Only one study has assessed the potential influence of changes in climate variability on the future of the boreal forest. Bugmann and Pfister (2000) used the model FORCLIM to explore the effects of long-term average vs. monthly mean variable climate at an elevation transect in the European Alps under both current and future climate scenarios. The model produced plausible results with variable climate and indicated strong forest sensitivity to changes in climate variability in the ecotonal areas.

The physiological responses of most boreal species to short-term climate variations is not well understood (Bonan and Shugart, 1989; Sykes *et al.*, 1996; Elliot-Fisk, 2000) and boreal patch models tend to rely heavily on empirically based parameterizations (correlations between climate variables and known species distributions). Since tolerances derived from correlations with current climate cannot be assumed to represent true physiological limitations (Bonan and Sirois, 1992; Lenihan, 1993; Norby *et al.*, 2001; Hickler *et al.*, 2004) the concern must remain that under conditions of future climate change, patch models such as FORSKA-2V may limit species from establishing in new climate spaces that do not match their current "climatic envelope" even though physiological growth might be possible (Fischlin *et al.*, 1995; Pearson and Dawson, 2003).

Nevertheless, patch models incorporate a wide range of information about the physical characteristics of each species and account for factors such as interspecies competition, disturbance, and soil properties (Bugmann, 2001). The more mechanistic "empirically-based" gap models such as FORSKA-2V have been much improved in recent years and have demonstrated an ability to respond to new combinations of forcings with ecosystem modifications such as changes in composition and dominance of species considered essential for examining impacts of future climate change (Lenihan, 1993; Price and Apps, 1996; Claussen *et al.*, 2003).

2.3 The FORSKA-2V Gap Model

The FORSKA2 patch model was developed to study forest ecosystems in Europe (Leemans and Prentice, 1989; Prentice *et al.*, 1993) and modified by Price *et al.* (1999a) to make it more suitable for studying central Canadian boreal forests. Model processes are well described and documented (Leemans and Prentice, 1989; Prentice and Leemans, 1990; Prentice *et al.*, 1993; Price *et al.*, 1999a).

Most gap models used today are based on the same general formulation as the initial gap model JABOWA introduced by Botkin *et al.* (1972b) and further developed by Shugart (1984) in the FORET model. The FORSKA2 model is considered to be one of the more mechanistic of the patch models (Lasch and Lindner, 1995; Lindner *et al.*, 1996; Bugmann and et al, 1996; Nalder, 2002). One important difference is that, unlike

JABOWA, FORSKA2 adopts more physiologically based responses to climate and the environment. In particular, new algorithms relate growth to the effects of daily temperature on photosynthesis and respiration and of leaf area on light assimilation, replacing the traditional relationship based only on growing degree sums and allometric relationships with diameter at breast height (DBH) (Botkin *et al.*, 1972b; Shugart, 1984; Botkin and Nisbet, 1992; Nalder, 2002). Representation of the effects of shading and competition for light is also improved by distributing leaf area throughout the canopy, as opposed to a flat disc at the top of the tree.

Most gap models account for soil water deficits in some way (Bugmann, 2001). In FORSKA-2V, drought is related to soil water potentials rather than soil water content as in FORSKA2 to reflect a non-linear decrease in availability of water to the tree as soil water content decreases (Price *et al.*, 1999a). This modification was deemed necessary in the central Canadian boreal region characterized by relatively low rainfall and high summer evaporative demand. In addition to the improved soil water balance model, further modifications by Price *et al.* (1999a) include an increase in establishment rates in the first year following a disturbance to reflect the frequent and large-scale wildfires characteristic of the boreal forest.

3 FORSKA-2V: MODEL DESCRIPTION

FORSKA-2V consists of a submodel to prepare the environmental information for the patch, and a submodel for tree population dynamics that determines each species' annual responses in terms of establishment, growth and mortality, as a function of the environment, competition and disturbance events on each patch.

3.1 The Environment Submodel

Climate and other input data are used to drive key processes related to surface energy balance, evapotranspiration and soil water balance modeled on a daily or hourly time-step. Soil moisture is calculated on a daily basis as the difference between daily total precipitation and losses to evapotranspiration and runoff. The plant-available soil water holding capacity (WATC) can be changed to represent different soil types, but the model does not account explicitly for the presence of frozen soil. Snow is considered as precipitation but does not accumulate above the capacity of the soil water "bucket".

Daily values of heat, light and available soil water are averaged over each simulated growing season to represent inter-annual differences in site environmental conditions. For instance, soil moisture affects tree growth and regeneration through an annual drought index computed by the model from the sum of daily soil water potentials over the growing season. Annual species-specific "multipliers" are derived from the daily effects of temperature on respiration and photosynthesis averaged over the year. Conifer tree species are considered to grow and respire when daily mean temperature exceeds –4°C, whereas deciduous species require daily mean temperatures above +5°C.

3.2 The Population Dynamics Submodel

Tree State Variables: Each individual tree on a patch is identified by its species type, stem diameter, top and bole height, leaf area, age, and annual growth efficiency (the annual stem volume increment per unit leaf area/species optimum growth).

Growth: A species' theoretical maximum growth rate is modified by climate dependent factors such as the number of growing degree days and the effects of daily temperature on photosynthesis and respiration and soil moisture. There is no growth if winters are too cold (Table 2). Net assimilation is further related to leaf area, species sapwood maintenance costs, and the effects of shading on the light regime. Annual growth is then allocated to height, diameter and leaf area. Bole heights increase based on the amount of light penetrating to leaf area at the bottom of the simulated canopy.

Annual Establishment: All species in the species list are assumed to have seeds available for establishment at all locations. If light at the forest floor and other environmental conditions are suitable a random number of new saplings (1.3m high with minimum initial diameter of 1 cm) are planted each year. A species' optimal annual regeneration rate is constrained relative to the degree that species-specific light, winter chilling and growing season warmth requirements are met, and cold tolerance is not exceeded (Table 2), conditions which vary from year to year.

Post-Disturbance Regeneration: A significantly larger number of seedlings are planted the first year following a disturbance to reflect the important role of natural disturbances, primarily fires, in stand regeneration in the central Canadian boreal forest.

Table 2. Summary of the model's representation of environmental controls on tree growth and establishment.

Function	*Model representation*
Species optimal growth rate (**GSC**) is modified by environmental factors:	AMDGSC=GSC*TCMX*GDDMX*TFTMX*DRMX
Species optimal establishment rate (**EST**) is modified by environmental factors:	AMDEST=EST*TCMX*TWMX*TWARMX *GDDMX*DRMX*PMX*TFTMX
If the mean temperature of the coldest month (TCOLD) is below the temperature that a species can tolerate (MINTC, e.g. = –25) growth and establishment will not occur:	IF(TCOLD.LT.MINTC) **TCMX**=0.0
If the mean temperature of coldest month (TCOLD) is greater than species winter chilling requirements (MAXTC, e.g. = -5.0) then no new establishment will occur:	IF(TCOLD.GT.MAXTC) **TWMX**=0.0
If the mean temperature of warmest month (TWARM) is below the minimum temperature required by a species in the growing season (MINTW, e.g. =7.5) there will not be sufficient summer warmth for tree regeneration:	IF(TWARM.LT.MINTW) **TWARMX**=0.0
Other temperature and precipitation impacts on growth and establishment are reflected in growing degree day requirements (**GDDMX**), effects of temperature on net assimilation (**TFTMX**), and the influence of drought (**DRMX**) over the growing season. The ratio of assimilation at the forest floor to assimilation in full light (**PMX**) also modifies establishment and growth.	

Competition for Resources: There is no direct competition for water and all species are assumed to have equal access to the water resources on the patch. However, competition for water is represented indirectly through species-specific sensitivity to drought and soil saturation. Light penetrating the canopy at a given height is reduced due to interception by the total leaf area on the patch above that height. Species growth and establishment depends on whether the available light is sufficient for assimilation and regeneration. Non-tree competitors such as shrubs and mosses are not considered and no interaction takes place between patches.

Mortality: Mortality is determined by an intrinsic mortality rate related to age and a higher extrinsic mortality rate is triggered if an individual tree's overall vigor falls below species specific annual minimum growth efficiency.

Disturbance: Various disturbance types can be considered by gap models but in FORSKA-2V the only disturbance type considered is stand-replacing wildfire. Disturbance is stochastic with an established mean return interval and probability of occurrence increasing linearly with time since last disturbance. Fire is assumed to destroy all trees on the patch.

Output: Stand density (stems/ha), biomass density (Mg/ha), basal area (m^2/ha), leaf area (m^2) and change in annual productivity (Mg/ha/yr) for each species, for each patch, and spatially-averaged output across all the patches are computed, including classification by diameter (cm), height (m), and age class, and softwood vs. hardwood distribution.

3.3 FORSKA-2V: Model Validation

Price and Apps (1996) used FORSKA2 to simulate forest response to current climate at eleven sites in central Canada. The model's response was considered reasonably consistent with observed species composition and biomass density. The researchers found relatively small change in species composition and biomass density under different scenarios of change in mean temperature and percent of total precipitation. In the north, where temperature is believed to be a primary limiting factor, future scenarios of warming had little effect, corroborating the conclusions of Bonan *et al.* (1992) that air temperature may not be the only major control at northern range limits. In the mid- and southern boreal regions, Price and Apps (1996) reported small increases in simulated biomass density under warmer climates, which they suggested was due to failure to account for the impact of climatic variability on soil water deficits. This apparent deficiency led to development of FORSKA-2V. An improved soil water balance sub-model and inclusion of inter-annual monthly variability in FORSKA-2V improved the model's ability to predict the current distributions of tree species at central Canadian boreal sites and produced plausible results under scenarios of climate change (Price *et al.*, 1999a; 1999b).

Bugmann *et al.* (2001) compared gap model performance at four boreal sites, three in central Canada and one in Québec. FORSKA-2V outperformed other gap models in simulating forest cover, species composition and biomass density at the central sites. It simulated changes in composition along moisture gradients under current conditions and projected shifts in vegetation zone with a change in mean climate. FORSKA-2V was thought to perform better than the other models due to a better representation of soil water balance, not least because it had been developed and tested in that region. The model performed reasonably well under current climate at a site where it had not been calibrated (Québec) but showed no sensitivity to climate change at this site. The authors suggest that this could be a legitimate response to the climate change assumed for the site, where annual precipitation remained high and was not considered limiting to growth. Nalder (2002) found that the model was prone to under-estimates of biomass and stand densities with current climate forcing at a northwest and a northeastern central Canadian boreal site and attributed low rates of seedling establishment and overestimated mortality to an oversensitive drought response. Further testing has been recommended to assess the suitability of the model for study outside of the region for which it was calibrated (Bugmann *et al.*, 2001; Nalder, 2002).

4 DATA AND METHODS

4.1 Site Selection

Environmental conditions for seven central Canadian sites were used in the model simulations. Sites were chosen to be representative of a larger range of central Canadian bioclimatic zones (Ecological Stratification Working Group, 1996) than previous studies (Figure 1, Table 3). The sites span the warmer and drier southwest to the cooler and moister northeast, and include one site each from aspen parkland/grassland (Rosthern), southern closed forest (Waskesiu Lake), central closed forest (Flin Flon), northern closed forest (Thompson), open forest (Fort Smith), forest-tundra (Ennadai Lake) and tundra (Baker Lake) (Larsen, 1980; Elliot-Fisk, 2000).

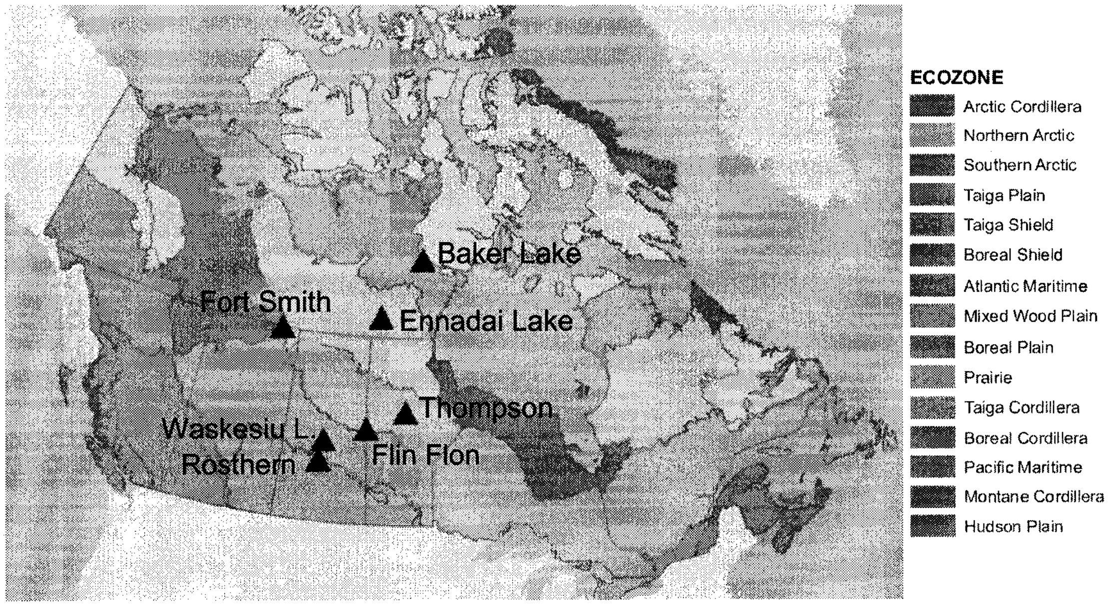

Figure 1. Ecozones and the location of the selected study sites. Ecozone map from the National Ecological Framework for Canada (2005) in Canada Lambert Conformal Conic projection.

Table 3. Location, average climate (1961-90 normals) and other key aspects of the study sites.

	Rosthern	Waskesiu Lake	Flin Flon	Thompson	Fort Smith	Ennadai Lake	Baker Lake
Latitude	52.67	53.92	54.77	55.80	60.02	61.12	64.30
Longitude	-106.32	-106.07	-101.87	-97.87	-111.95	-100.90	-96.07
Mean elevation (m)	509	545	320	222	205	340	18
Mean Annual Temperature (°C)	1.1	0.4	-0.9	-2.4	-3.3	-11.7	-12.2
Mean Annual Precipitation (mm)	397.50	440.80	490.80	497.20	334.40	358.40	261.80
Degree-days (+5°C)	1439	1261	1251	1113	1026	432	348
Est. Anuual PET (mm)	530.92	510.24	497.89	473.78	490.99	372.16	382.66
Sunshine Hours (%)	50	48	46	44	42	40	36
Ecozone	Prairie	Boreal Plains	Boreal Shield	Boreal Shield	Boreal Plains	W. Taiga Shield	Southern Arctic
Forest Cover	grassland-forest	southern closed forest	central closed forest	northern closed forest	open mixed forest	forest-tundra	tundra

4.2 Model Input Data

Inputs required for simulation include site-specific climate variables (maximum and minimum temperature, precipitation, and sunshine hours), soil water holding capacity, disturbance regime characteristics; and a large number (25) of species-specific parameters.

Climate Data

Records of daily maximum and minimum temperature (°C) and total precipitation (mm) were obtained from Environment Canada for climate stations at Rosthern (SK), Waskesiu Lake (SK), Flin Flon (MB/SK), Thompson (MB), Fort Smith (NWT), Ennadai Lake (NU) and Baker Lake (NU). For each of the seven climate stations, monthly mean and constant (long-term average monthly mean) temperature and precipitation totals and their variances were computed from the daily data over the length of available time series.

Each data set was repeated in sequence to create a 1200 year time series to preserve autocorrelation and structure for each variable and (in the case of daily data) to preserve covariance among variables. The percentage of sunshine hours each day was derived from the ratio of total monthly bright sunshine hours (Marshall and Schut, 1999) to total monthly daylight hours at each site computed using standard models (D.T. Price, Canadian Forest Service, pers.comm.).

Soil Water Holding Capacity

Maps of plant-available soil water holding capacity, resampled from the Agriculture Canada Soil Landscapes of Canada (SLC) database, were obtained from Liu *et al.* (2002). Data from the grid cells containing the locations of the seven climate stations were used to represent soil texture (e.g. sand, silt and clay volume fractions) at those station locations. A "reference" soil water holding capacity (variable name WATC in FORSKA-2V) considered representative of each site was determined using the SLC polygons, local site descriptions available in the literature and the results of model sensitivity tests (Table 4).

Table 4. Reference soil water holding capacity (WATC) reference levels for each site.

Site	Reference WATC (mm)	SLC Polygons (mm)
Rosthern	120	100-150
Waskesiu Lake	150	100-150
Flin Flon	150	50-150
Thompson	200	50-250
Fort Smith	150	50-150
Ennadai Lake	150	0-150
Baker Lake	100	0-150

Species Parameters

The life history and climatic requirements of the boreal tree species included in this study (Table 5) follow those reported in Price *et al.* (1999a) and Price and Apps (1996), many of which are based on range maps from Burns and Honkala (1990a) and as reported by Botkin and Nisbet (1992) for JABOWA-2.

Forest Data

Information on observed species composition and forest growth at the seven sites (needed to interpret model results) was gathered from available documentation. The vegetation classification of the Ecological Stratification Working Group (1996) was used to identify large-scale vegetation patterns across the ecozones in which each site is located. Aboveground biomass density data from the Canadian Forest Inventory (Lowe *et al.*, 1994) was transformed to 10km grid cells at the location of the Rosthern, Waskesiu Lake, Flin Flon, Thompson and Fort Smith climate stations (D.T. Price and M. Siltanen, Canadian Forest Service, pers.comm). Supplementary data for Rosthern was obtained from field observations made by Hogg (1999), and for Waskesiu Lake, Thompson and Fort Smith from observations of Nalder and Wein (1999). Field data from forested sites at Waskesiu Lake, Flin Flon, Thompson was also well documented and available from the BOREAS project (Halliwell and Apps, 1997). The forest-tundra vegetation at Ennadai Lake was assessed based on qualitative descriptions of the Ecological Stratification Working Group (1996) and from field research conducted by Larsen (1965). Baker Lake is considered to be non-forested tundra.

Table 5. The ten boreal tree species used in this study.

Species name	**Common name**	**Abbreviation**
Abies balsamea	balsam fir	ABBA
Betula papyrifera	white birch	BEPA
Larix laricina	tamarack	LALA
Picea glauca	white spruce	PIGL
Picea mariana	black spruce	PIMA

Pinus banksiana	jack pine	PIBA
Pinus strobus	eastern white pine	PIST
Populus balsamifera	balsam polar	POBA
Populus tremuloides	trembling aspen	POTR
Thuja occidentalis	eastern white cedar	THOC

4.3 Model Application and Assessment

Model Application

Basic Initialization: The model was initialized from bare ground (Smith, 2001; Lindner, 1996) and forced with a 1200 year time series created from the historical daily, monthly mean and constant climate record for each site. Forest development was simulated on 200 replicate patches of 0.1 ha at each site. A size of 0.1 ha is considered by many to be an appropriate patch size for modeling boreal forest gap dynamics as it provides a gap large enough to allow light to penetrate to the forest floor (Bonan and Shugart, 1989; Prentice and Leemans, 1990). Simulations of 400 years or longer are considered necessary to reach stable outputs Prentice *et al.* (1993). Given the large number of stochastic parameters (e.g. establishment, mortality, disturbance), it is common practice to simulate a large number of patches (typically 100-200) to ensure simulation of a wide range of possible outcomes and for the model to exhibit its central tendency for a given set of conditions (Fischlin *et al.*, 1995; Bugmann, 2001). The mean return interval for stand-replacing fires was set to 100 years, a widely used average for the boreal forest.

Soil Water Holding Capacity: Simulations at the reference WATC (Table 4) are the main focus of analysis at each site and the basis for comparative analysis between sites. Additionally, given the potential for considerable small-scale spatial variability in soil properties and that vegetation typically varies in relation to soil conditions (Fowells and Means, 1990), the model's response to variations in WATC were also closely assessed.[1]

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[1] Some studies have assumed the water holding capacity of the soil is identical at all sites (Price and Apps, 1996). Others have used an average of field measurements (which may vary over the site) as the input variable (Nalder, 2002) or averaged the results from simulations using two or more appropriate soil classes for each site (Lindner *et al.*, 1996). These approaches do not support assessment of the simulated response of vegetation to varying soil conditions known to be an important control on actual vegetation distribution (Fowells and Means, 1990).

At each site, simulations with WATC set to 120 (representing drier soils, i.e. coarse-textured soils with relatively low water holding capacity), 150 (representing more mesic soils) and 200 mm (representing wetter soils, i.e. deep and fine-textured soils with relatively higher water holding capacity) were performed. Additional simulations were carried out for Rosthern and Thompson with WATC set to 100 and 250 mm, respectively.

Atmospheric Carbon Dioxide: Carbon dioxide fertilization effects were switched off to investigate climate effects only. Background atmospheric $C0_2$ was set to 340ppm, approximately the mean global concentration during the twentieth century (Smith *et al.*, 2001; IPCC, 2001).

Assessment of Results

Forest development (the new species "equilibrium") is described as the spatially-averaged output of 200 replicate patches over 200 years of simulation following stabilization (Lindner *et al.*, 1996; Price *et al.*, 1999a; Bugmann, 2001). Patches were also sorted and averaged by age-class to retain important information on variation of patches with different successional ages (Price *et al.*, 1999b; Risch *et al.*, 2005). Modeled variables used as criteria to describe forest structure include total site biomass density and the proportion of hardwood and softwood biomass and stem densities. Variables used to describe species composition and growth include species-specific biomass and stem densities.

The model's generality was assessed by evaluating the effect of different resolution climate input data on the pattern of simulated total biomass and the proportion of hardwood and softwood biomass and stem densities compared to the observed patterns of forest structure along the modeled bioclimatic transect. The model's accuracy was assessed by evaluating the effect of different resolution climate input data on simulated

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species composition and species-specific biomass and stem densities compared to field observations at each site.

Testing the behavior of the model with the use of daily data compared to monthly or constant climate data is the major purpose of this study and quantitative comparison with field data is of secondary importance. Nevertheless, this study uses several different data sets to estimate spatially-averaged biomass density and species composition at each site and undertakes a more rigorous quantitative comparison of the simulated results to the observed data than many previous studies. Describing the statistical significance of the impact of daily data on the indicator variables compared to use of other resolution climate data is not practical without more comprehensive (spatially-averaged and age-class structured) field data.

5 MODEL MODIFICATIONS

The FORSKA-2V model, as modified below for the purpose of this study, is hereafter referred to as FORSKA-2V+. The FORSKA-2V+ model code is included in Appendix 6.

For this study, FORSKA-2V was configured to compile on a PC running Windows rather than a UNIX platform and considerable debugging of program code was required. In the population submodel, a number of inaccuracies in the program code were corrected, including the tracking of disturbances and updating patch ages following a simulated disturbance event. Errors in the calculation of biomass density and deadwood biomass and inconsistent use of units were corrected in the output routines.

Use of Climate Input Data

The environmental submodel, including the daily-time step processes, was modified for use with actual (as opposed to interpolated) daily climate input variables and improvements were also made to the algorithms used to read in monthly mean data.

Sprouting

Initial simulations indicated that running the model with sprouting disabled made no difference to simulated outcomes despite the importance of this regeneration strategy for most hardwoods. Following an in-depth assessment of the sprouting algorithm, errors were identified in the model code that in effect "stranded" new sprouts from the inventory of individuals on a plot, resulting in them never being included in subsequent stand development. These errors were corrected.

Post-Fire Succession

The FORSKA-2V model used as the initial basis for this study includes a modification intended to reflect rapid post-fire establishment of seedlings that is characteristic of the Canadian boreal. The modification increases all species' establishment rates in the first year following a disturbance by a factor of 50 (Price *et al.*, 1999a; Bugmann *et al.*, 2001).

However, the results of initial simulations indicated an unrealistic simulated dominance of white spruce and a low proportion of hardwood species, particularly in the early stages of succession. For instance, despite being the dominant hardwood at Waskesiu Lake simulated aspen density was low at this site. It established fewer individuals than other species following a disturbance and then quickly diminished. White spruce on the other hand, which should require many decades to dominate the canopy, established rapidly following disturbance and soon dominated the other species (Figure 2a). However, with the FORSKA-2V post-fire modification removed, white spruce and jack pine (because of a higher establishment rate parameter) continued to quickly dominate hardwoods post-disturbance (Figure 2b). Post-fire regeneration dynamics are clearly important and need to be included, but revision of the original modification was required.

The FORSKA-2V modification gave all species the same post-fire "rapid establishment" advantage. However, not all species exhibit rapid regeneration following a disturbance. Fire events typically provide more optimal conditions for the rapid establishment of species that produce serotinous cones and that require fire for the release of seeds (such as jack pine and to a lesser extent black spruce) and for broadleaved trees such as aspen that produce sprouts when the aboveground portions have been killed by fire or drought (Peterson and Peterson, 1992; Seymour, 1995; MacDonald, 2003). In comparison, white spruce is a late-successional species that seeds in gradually (Suffling, 1995) and may remain as part of the understory for 50 to 70 years (Burns and Honkala, 1990b; Rook, 2006).

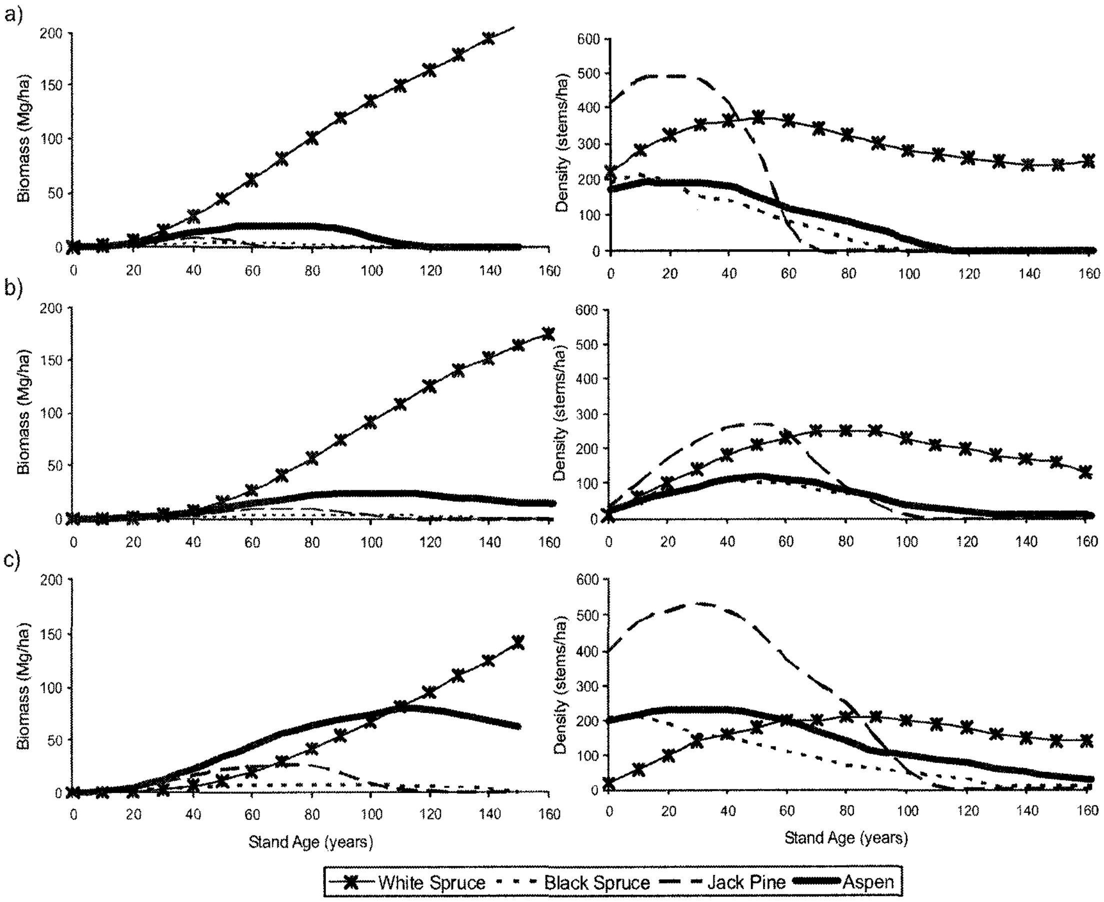


Figure 2. Simulated spatially averaged biomass (left) and stand densities (right) illustrating species succession over time at Waskesiu Lake with a) FORSKA-2V modification favoring rapid regeneration of all species following fire; b) no modifications to species relative post-fire regeneration; and c) FORSKA-2V+ modifications favoring the three most aggressive post-fire pioneers (jack pine, aspen and black spruce). Simulations are with daily climate input data and WATC of 150mm.

The model was therefore modified to enhance the rapid post-fire regeneration of only the three most aggressive post-disturbance pioneers – *jack pine, aspen and black spruce.* This modification significantly reduced the simulated biomass and stem densities of white spruce and the resulting successional pattern became more realistic. Jack pine, aspen and to a lesser extent black spruce establish rapidly following a disturbance. White spruce establishes gradually, succeeding aspen after around 70 simulated years (Figure 2c). The proportion of hardwood biomass density in the species mix along the transect was also improved. The new "post-fire regeneration" modification was found to improve the realism of simulations at all sites and was therefore adopted for use with the FORSKA-2V+ model in this study.

6 RESULTS

6.1 The impact of climate variability on the modeled environment of a patch

Traditional input variables to the FORSKA2 model include monthly climate records, which are either long-term averages or multi-year records of monthly mean temperature (including monthly average daily temperature range (or Tmin and Tmax)) and total precipitation. When using monthly mean data, the daily temperature values used for daily time-step processes are derived by simple linear interpolation between successive monthly mean values. Even though the monthly averages were computed from the daily data and therefore share the same long-term mean, interpolation from monthly averages does not capture day-to-day variability and extremes (Figure 3).

Many processes captured in the FORSKA2 model are simulated on a daily time-step, which suggests that it has the potential to simulate responses to the impacts of climate variations and extremes observed at daily time scales. As a first step, it is important to understand how the use of daily data affects the behavior of the model as it is currently designed and how the simulated environmental controls on a modeled patch differ compared to when the model is forced with monthly means.

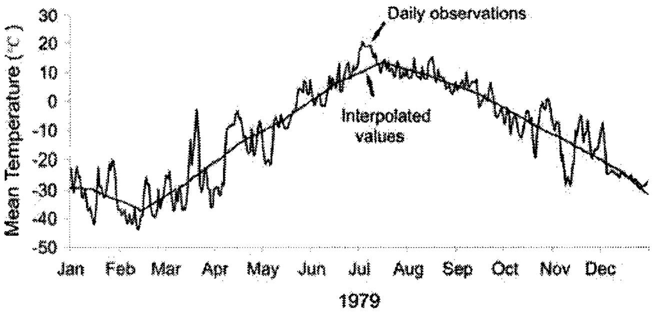


Figure 3. Comparison of the daily mean temperature values used to drive the daily time-step processes in FORSKA-2V+ when using daily climate observations (variable line) versus daily values derived by interpolation between monthly means (straight line). Example is from Ennadai Lake climate record, 1979.

The effects of daily temperature and precipitation on the soil-water balance sub-model

The soil-water balance is perhaps the most sensitive environmental process directly affected by the use of daily data in the model. When forced by monthly precipitation totals, daily precipitation inputs to the soil water "bucket" are determined by allocating the monthly total equally among every day in the month, thereby eliminating the impacts of any variability over this period. However, precipitation is typically unevenly distributed over time and the use of actual daily totals shows considerable day-to-day variability and extremes in rain and snowfall (Figure 4).

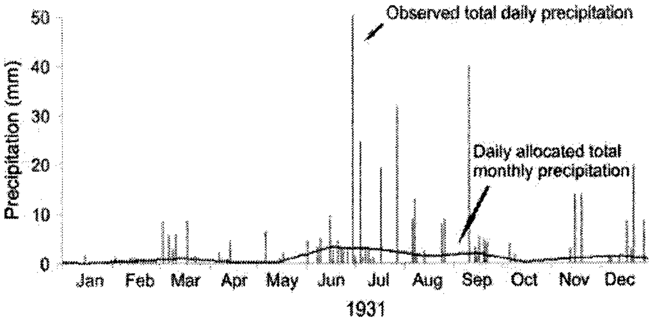
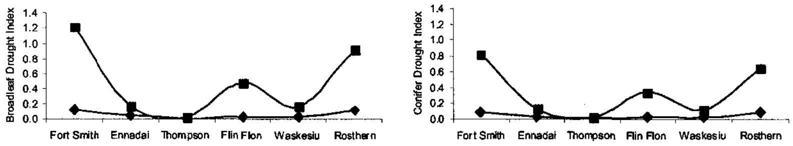


Figure 4. Comparison of daily precipitation values used to drive the daily time-step of the soil-water balance sub-model in FORSKA-2V+ when using actual daily precipitation totals (bars) versus those derived by allocating the monthly total equally to every day in the month (line). Example is from Rosthern climate record, 1931.

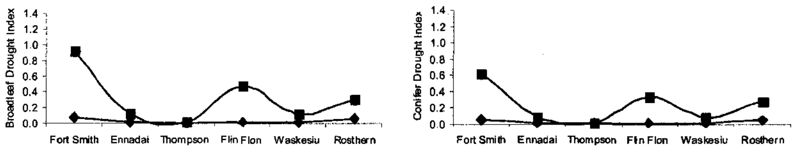
Using daily temperature data also affects simulated soil moisture availability as a driver of actual evapotranspiration (AET) which is calculated on a daily time-step in FORSKA-2V+. For instance, at the Rosthern site, when the model is driven by daily data, total monthly potential evapotranspiration (PET) during summer months generally exceeds

PET calculated from monthly mean data because the monthly temperature sums are larger. AET, however, is typically lower because of the impact of variable precipitation on soil water availability and because of the non-linear relationship imposed between soil water content and soil water potential which feeds back on simulated transpiration. The general effect of variations in daily temperature and precipitation on soil water balance is an increase in the subsequent frequency and intensity of simulated drought events compared when monthly mean or constant climate input data is used (Figure 5).

a) Daily Climate



b) Monthly Mean Climate



c) Constant Climate

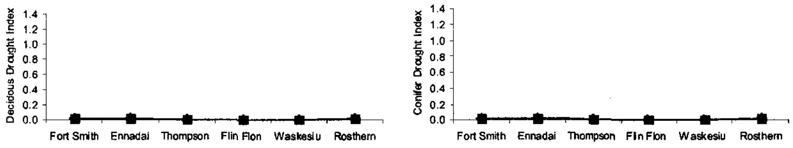


Figure 5. Simulated mean (diamond) and maximum (square) broadleaf (left) and conifer (right) annual drought indices with (a) daily, (b) monthly mean and (c) constant climate input data. Simulations are with WATC set to reference levels with the exception of Fort Smith with WATC set to 120mm.

The effects of daily temperature on growing degree days (GDD)

Growing degree days (GDD) are calculated by integrating daily mean temperatures over a pre-determined reference temperature (usually 5°C, as used in this study). Interpolating daily temperatures from monthly data results in the averaging out of extremes that can make a substantial difference to total temperature sums at a site. To illustrate, at the northern Ennadai Lake site the use of daily data generated significantly more growing degree days than were obtained from using interpolations derived from monthly mean temperature data (Figure 6). In fact, at Ennadai Lake, the underestimation of GDD calculated from monthly means was found to eliminate simulated growth at this site when the model was forced with monthly mean climate data, compared to realistic simulated species composition and growth when forced with the daily climate data (section 6.3.5).

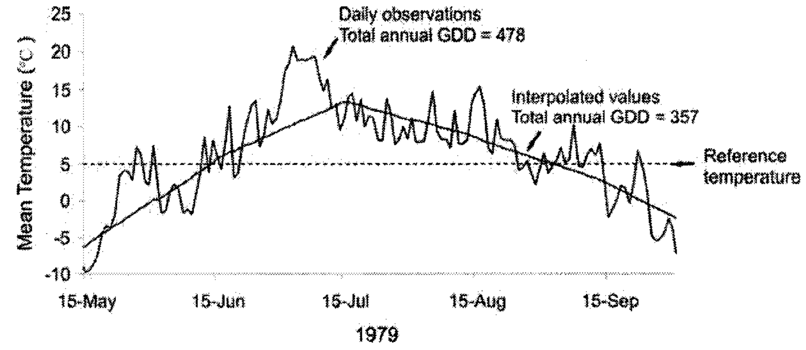


Figure 6. Comparison of the growing degree days (GDD) simulated at Ennadai Lake (1979) when using daily climate observations (variable line) versus daily values interpolated from the monthly mean data (straight line). Dotted line at 5°C is the reference temperature used in this study.

Growing degree days (GDD) calculated from monthly means are known to underestimate those calculated correctly from daily values (Marshall and Schut, 1999) and a shortfall of 10% is sometimes assumed (Fischlin *et al.*, 1995; Nalder, 2002). However, further investigation revealed that although underestimation of GDD at the central and southern sites is in fact close to 10%, at Ennadai Lake interpolations from the monthly climate record underestimate the total number of GDD by nearly 20% (Table 6).

Table 6. The underestimation (%) of growing degree days (GDD) at each site when calculated from monthly means compared to GDD derived directly from daily climate observations.

Site	Latitude (DD)	GDD underestimation (%)
Rosthern	52.67	8.98
Waskesiu Lake	53.92	9.51
Flin Flon	54.77	9.28
Thompson	55.80	12.59
Fort Smith	60.02	11.17
Ennadai Lake	61.12	19.11
Baker Lake	64.30	23.16

On average, at the Ennadai Lake climate station 586 GDD per year are simulated using the actual daily climate record compared to 474 per year with the monthly record. Yet, it is not only the low average number of GDD that impedes simulated growth at this site, but its combination with variability. The average number of GDD derived from simulation with the constant climate is even lower (460 GDD) than for the simulations with the monthly mean climate. However, with the monthly record there is large year-to-year variability in simulated GDD, with some years less than 400 GDD and occasionally even fewer than 300 GDD. This is below the required minimum for growth and establishment as prescribed for some species in the study. Despite somewhat greater variability, the GDD sums derived from the actual daily observations are on average 20% higher to begin with and rarely fall below these thresholds (Figure 7).

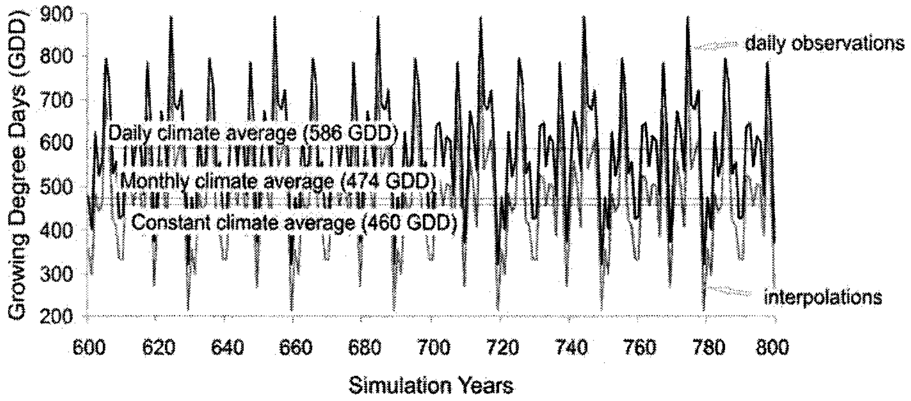


Figure 7. Annual growing degree days (GDD) for 200 simulated years (600-800) at Ennadai Lake calculated from daily observations (black line), monthly means (gray line) and constant climate (straight line at y=460 GDD), and the average annual simulated number of GDD with each of the three climate records.

Species multipliers

The use of daily temperature affects simulated daily photosynthesis and respiration, represented by the three "species thermal multipliers" (section 3.1). Total photosynthesis tends to be higher when the model is forced with variable daily temperatures, but respiration rates also respond accordingly (increasing exponentially with increasing temperature, (Fowells and Means, 1990), so net primary production may actually decrease compared to values simulated using monthly climate data.

Extreme temperatures and species tolerances

The mean temperature of the coldest month (TCOLD) and the mean temperature of the warmest month (TWARM) can be substantially different when derived from long-term averages versus multi-year records of monthly mean temperatures. The difference in the calculated mean temperature of the coldest month, for example, can influence whether the climatic potential for simulated growth and establishment of a species occurs or not (Figure 8).

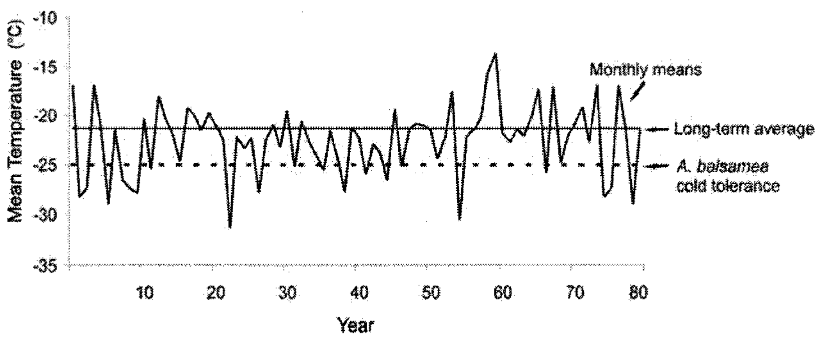


Figure 8. Mean temperature of the coldest month of the year (TCOLD) derived from long-term averages versus multi-year observations of monthly mean temperatures at Flin Flon (80-year climate record). In the model, the lowest mean monthly temperature that balsam fir (*Abies balsamea*) can tolerate before growth and establishment is compromised is -25°C.

Species parameters based on tolerances to daily climate extremes were not available. Accordingly, species temperature tolerances used in this study were derived from the monthly mean temperature isolines and precipitation totals which delimit a species range (determined empirically by comparing isolines to species range maps). In other words, the "extremes" against which species threshold tolerances are tested are still estimated from monthly means, even when the revised model is otherwise forced with a daily climate record. Despite this limitation, the assessment above demonstrates that variable temperature and precipitation data control model processes in a number of important ways that in turn can affect species establishment, growth and survival response.

6.2 The impact of climate variability on simulated forest structure along the transect

For each of the seven selected sites, the model was forced with the three different resolutions of climate data and the simulation results were compared to test the ability of the model to reproduce large-scale patterns in forest structure (total biomass density and the proportion of hardwood and softwood) along the transect.

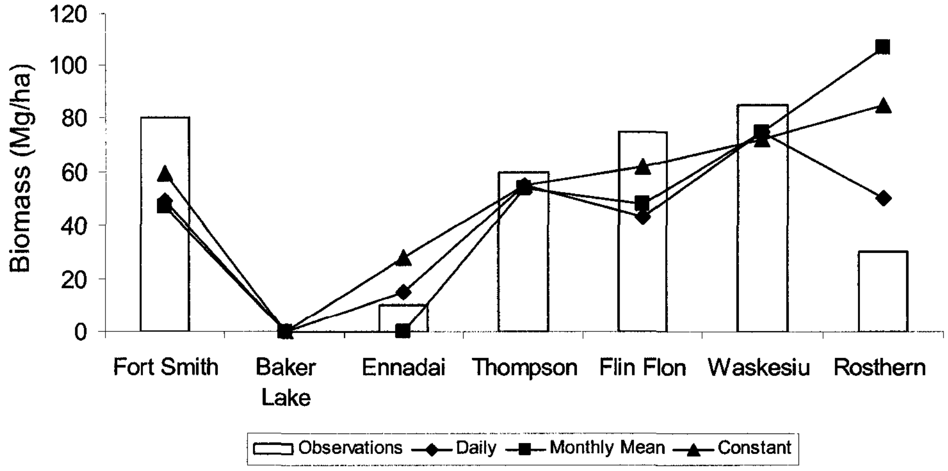


Figure 9. Simulated total biomass density at each site along the transect compared to observations. Simulations are with FORSKA-2V+ forced with daily (diamond), monthly mean (square) and constant (triangle) climate (lines are visual guide only). Totals are spatially-averaged over 200 simulated years with WATC set to the reference level at each site.

The constant climate provided plausible estimates of total biomass density for the central sites (Waskesiu Lake, Flin Flon, Thompson and Fort Smith), but failed to do so at the ecotonal sites (Ennadai Lake and Rosthern). Monthly climate data also provided good estimates at the central sites, although slightly lower than with the constant climate, but greatly overestimated biomass density at Rosthern and failed to simulate any forest growth at the Ennadai Lake site. There is little difference between forcing with the daily and monthly climate records at the central sites but only the forcing with daily climate simulated realistic biomass density at the two ecotones. When forced with the daily climate the simulated forest structure agrees with the actual patterns along the entire transect comparatively well. Forcing with all climate records resulted in overly low simulated biomass density compared to observations at the central site of Flin Flon and at Fort Smith. The constant climate produced slightly better estimates for these two sites but as will be discussed later, the associated simulated species composition was not as realistic. No trees were simulated at the Baker Lake site under any forcing scenario, in agreement with the treeless shrub tundra that is characteristic of this site (Figure 9). This control site was therefore not included in the subsequent analysis.

The simulated ratio of hardwood to softwood biomass density across the transect was consistent with expected values when the model was forced with either of the daily and monthly climate data sets (Figure 10). In both cases, more hardwood (aspen) was simulated at Rosthern, the aspen-parkland site, than at any other site, consistent with the observed dominance of hardwoods at this site. Simulations forced with the constant climate data did not reproduce the expected variations in the proportion of hardwood and softwood biomass density along the transect, even at the central sites where the constant climate provided good estimates of total site biomass density. Further, the proportion of hardwood was overly low at the southern ecotone, and too high at the northern ecotone, compared to observations.

The total stand density simulated at all sites was systematically low compared to field observations and none of the different climate forcings resulted in a discernable trend in hardwood to softwood stem density along the transect. In general, a 25-30% ratio of hardwood was simulated regardless of climate forcing or site. Forcing with the daily and monthly mean climate resulted in slightly better estimates at the ecotones. Resolving the issue of low simulated stand densities and the absence of a strong trend in hardwood to softwood proportions is examined further in the Discussion.

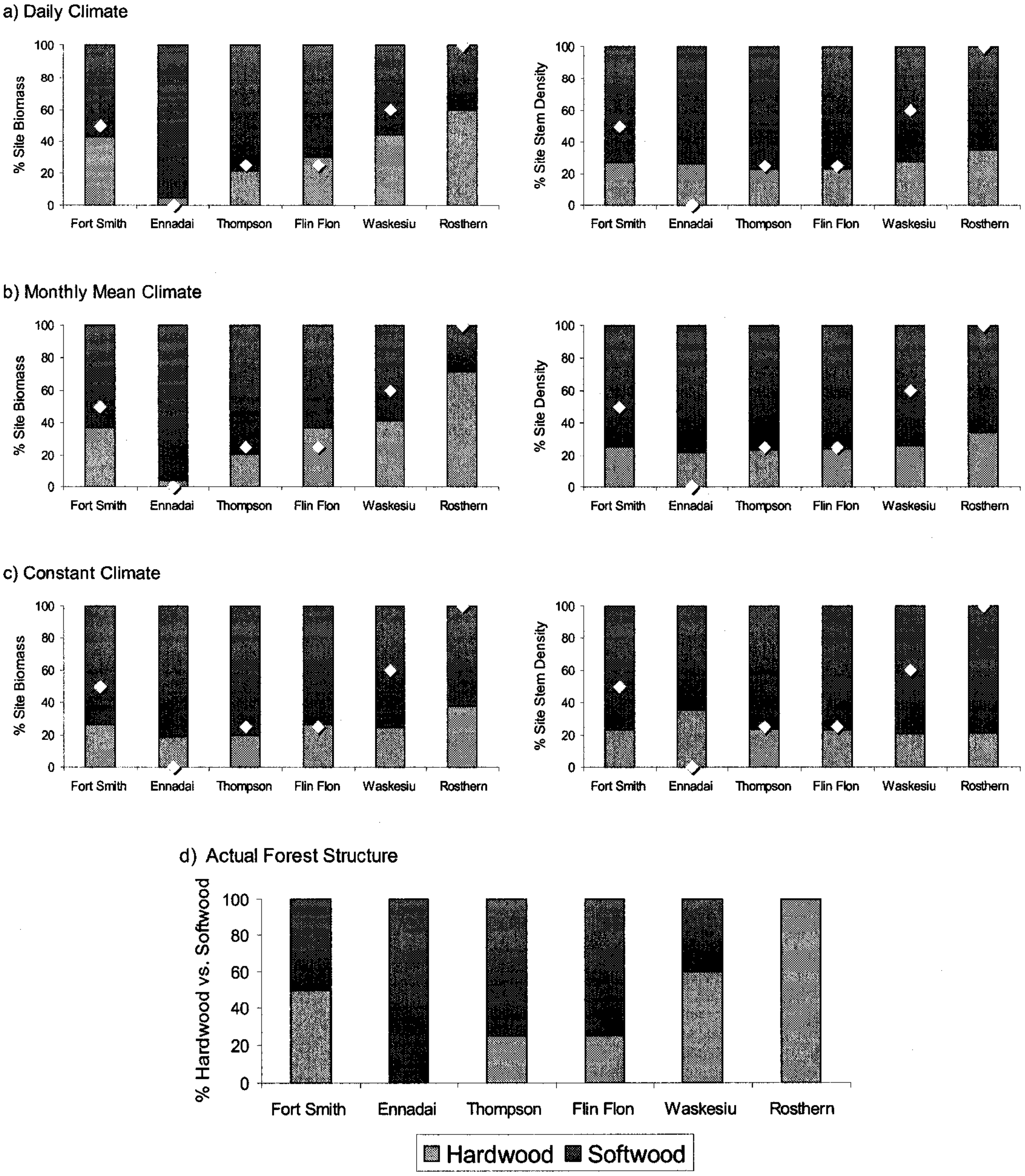


Figure 10. The ratio of simulated hardwood to softwood biomass (left) and stem (right) densities at each site along the transect with the FORSKA-2V+ model forced with a) daily, b) monthly mean and c) constant climate compared to d) actual forest structure (reported vegetation fractions, (Marshall and Schut, 1999). Markers on (a) to (c) denote the observed ratios at each site. Simulations are with WATC set to the reference level at each site.

6.3 The impact of climate variability on species-specific characteristics at each site

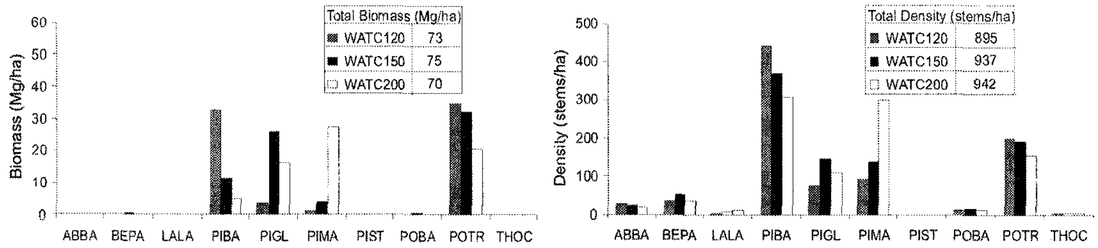
6.3.1 Waskesiu Lake

Waskesiu Lake is located in the boreal mixedwood region of Saskatchewan where many of the boreal species considered in this study are present. Aspen is the dominant taxon, with jack pine, black and white spruce, and small proportions of balsam poplar also present (Halliwell and Apps, 1997; Bugmann *et al.*, 2001). White spruce is considered the climax species that will generally succeed aspen in the absence of fire, insect attacks or drought.

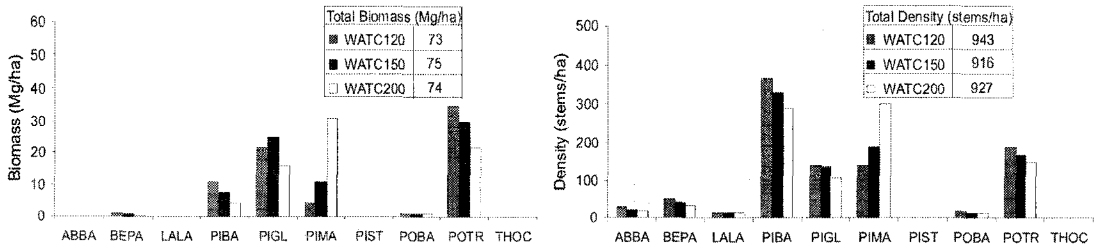
The simulated total site biomass density agreed closely with inventory data (Figure 9) and the expected dominant species are strongly represented in the simulated species composition (Figure 11) with each of the three climate forcings. The simulated proportion of hardwood biomass density approached expected values with both the daily and monthly climate forcing (Figure 10 and Appendix 3). Further, with daily climate input data, the model predicted a mixed forest that varied realistically with different soil WATC. Drier soils (represented here with WATC = 120 mm) are dominated by aspen-pine forest, although the model appeared to overestimate jack pine biomass density compared to observed data. More mesic soils (WATC = 150 mm) were predicted to support white spruce-aspen forest with some black spruce and jack pine. Black spruce with jack pine was simulated for wetter soils (WATC = 200 mm). The results obtained by forcing the model with monthly climate data differed little from those obtained with the daily climate with the exception that on the soils with the lowest WATC, aspen with white spruce, rather than with jack pine, was predicted to dominate stand biomass density.

The constant climate inaccurately predicted a forest dominated by black spruce at this site. The proportion of hardwood was low and the simulated species assemblage included a large proportion of eastern white cedar which is not naturally present in the region. There was virtually no sensitivity of the simulations to different levels of WATC and black spruce was abundant even when WATC was set to 120 mm. The relative stem density of jack pine compared to other species is high in simulations with all climate forcings (Figure 11).

a) Daily Climate



b) Monthly Mean Climate



c) Constant Climate

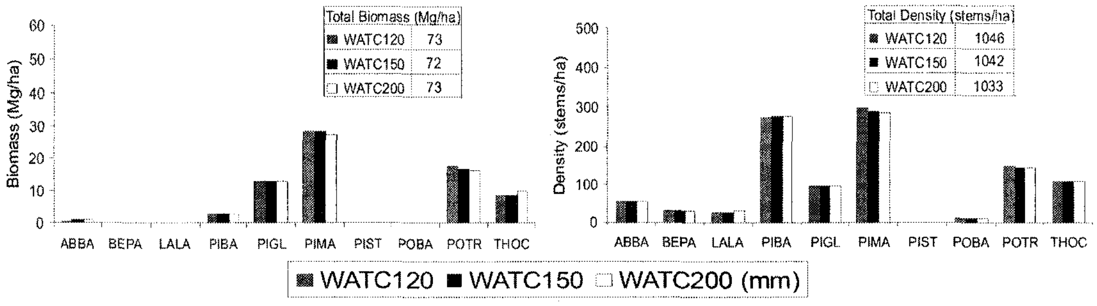
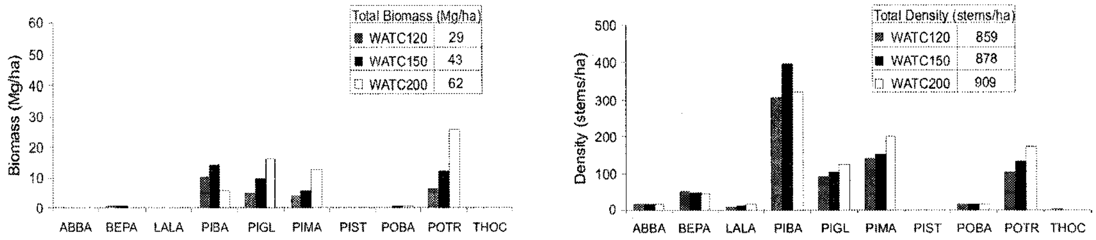


Figure 11. Simulated species biomass and stem densities for Waskesiu Lake with FORSKA-2V+ forced with (a) daily, (b) monthly mean and (c) constant climate input data with WATC from left to right of 120 (gray), 150 (black) and 200 (white) mm. Reference WATC is 150mm. Species abbreviations: *Abies balsamea* (ABBA), *Betula papyrifera* (BEPA), *Larix laricina* (LALA), *Picea glauca* (PIGL), *Picea mariana* (PIMA), *Pinus banksiana* (PIBA), *Pinus strobus* (PIST), *Populus balsamifera* (POBA), *Populus tremuloides* (POTR), and *Thuja occidentalis* (THOC).

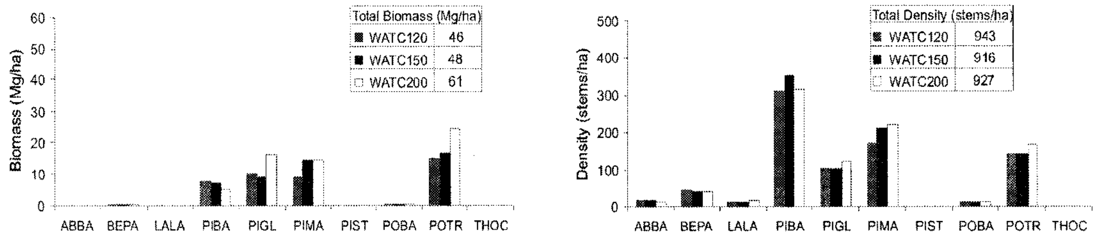
6.3.2 Flin Flon

Forest cover in the region surrounding Flin Flon is predominately coniferous. Black spruce, jack pine and aspen dominate with smaller amounts of white spruce and some paper birch and tamarack. Flin Flon is on the boundary between the Boreal Plains and the Boreal Shield ecozones. Soil conditions to the north and east (on the shield rocks) are generally very different from those to the south and west (boreal plains). On the shield, the forest canopy is more open and jack pine dominates the shallow mineral soils with low WATC with some aspen and spruce. To the south and west there is closed forest with relatively deep organic soils with black spruce and aspen dominating.

a) Daily Climate



b) Monthly Mean Climate



c) Constant Climate

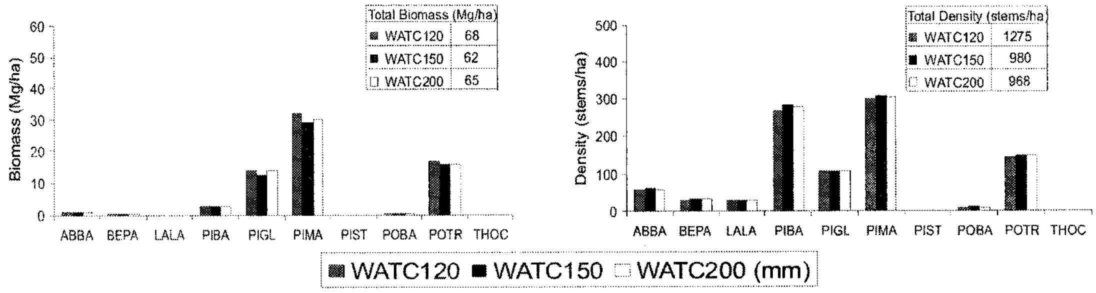


Figure 12. Simulated species biomass and stem densities for Flin Flon with FORSKA-2V+ forced with (a) daily, (b) monthly mean and (c) constant climate input data with WATC from left to right of 120 (gray), 150 (black) and 200 (white) mm. Reference WATC is 150mm. Species abbreviations: *Abies balsamea* (ABBA), *Betula papyrifera* (BEPA), *Larix laricina* (LALA), *Picea glauca* (PIGL), *Picea mariana* (PIMA), *Pinus banksiana* (PIBA), *Pinus strobus* (PIST), *Populus balsamifera* (POBA), *Populus tremuloides* (POTR), and *Thuja occidentalis* (THOC).

The total site biomass density simulated with the daily, monthly mean and constant climate data sets were low compared to reported values, with the constant climate producing the highest and the daily climate the lowest (Figure 9). When soil water holding capacity was set to 200 mm, simulated biomass density estimates from the three climate data sets converged and were more consistent with the observations. The proportion of hardwood to softwood biomass density was simulated well with all climate data sets (approximately 30-70%, respectively).

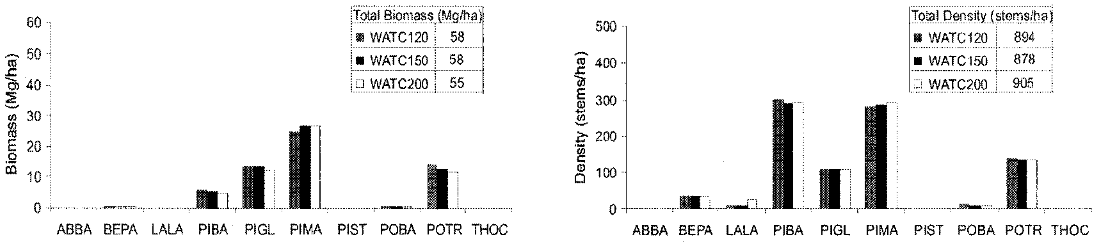
Simulations forced by the constant climate data set resulted in a larger proportion of black spruce biomass density, but less jack pine, than obtained using monthly or daily climate, and species biomass and stem densities did not respond appreciably to changes in WATC. Increasing climate variability (i.e., from constant to monthly mean to daily climate data) led to an overall reduction in black spruce biomass density at all levels of WATC and an increase in aspen on soils with WATC of 200mm. Black spruce biomass density is particularly low in simulations with the daily climate. The relative stem density of jack pine compared to other species is high in simulations with all climate forcings (Figure 12).

6.3.3 Thompson

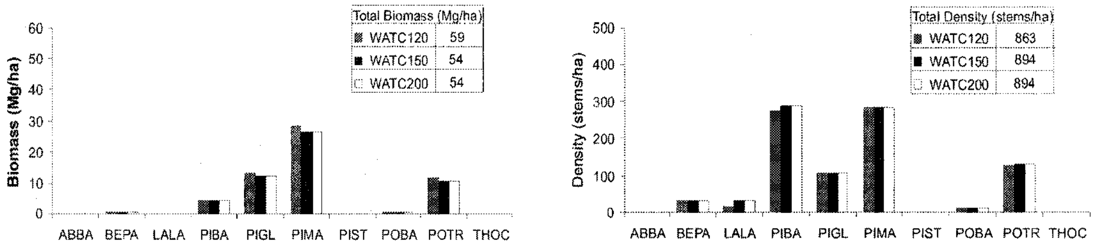
Forest cover in the Thompson region is mainly coniferous. Black spruce dominates in much of the area, although jack pine and aspen are also common, particularly on locally elevated plateaux. Other boreal species contribute only small proportions of vegetation cover.

Simulated total site biomass density with all three climate forcings was consistent with the measured data reported for the site (Figure 9). The proportions of hardwood to softwood biomass density and stem density approached the 25-75% mix expected in this region (Figure 10 and Appendix 3) with little difference in the simulated ratios regardless of the climate data set or value assigned to WATC. Simulations at WATC 250mm yielded similar results. Simulations with all climate series resulted in an appropriate relative abundance of the three dominant species (black spruce, aspen and jack pine) (Figure 13).

a) Daily Climate



b) Monthly Mean Climate



c) Constant Climate

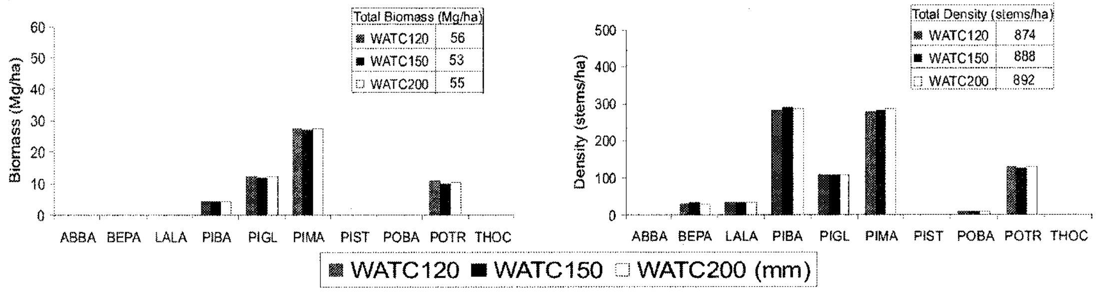


Figure 13. Simulated species biomass and stem densities for Thompson with FORSKA-2V+ forced with (a) daily, (b) monthly mean and (c) constant climate input data with WATC from left to right of 120 (gray), 150 (black) and 200 (white) mm. Reference WATC is 200mm. Species abbreviations: *Abies balsamea* (ABBA), *Betula papyrifera* (BEPA), *Larix laricina* (LALA), *Picea glauca* (PIGL), *Picea mariana* (PIMA), *Pinus banksiana* (PIBA), *Pinus strobus* (PIST), *Populus balsamifera* (POBA), *Populus tremuloides* (POTR), and *Thuja occidentalis* (THOC).

6.3.4 Fort Smith

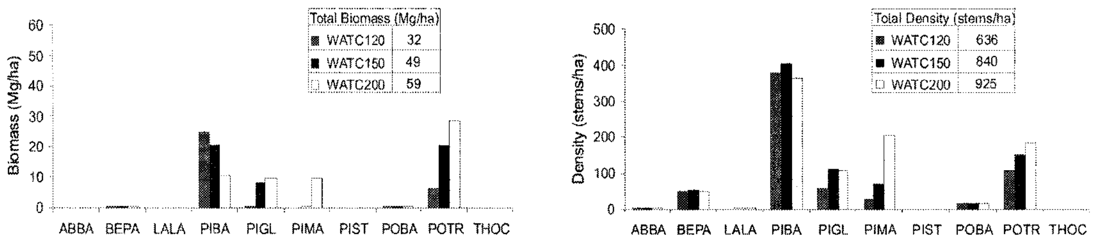
Fort Smith is located at the transition between the Boreal Plains and the Taiga Shield ecozones. Forest type is varied, consisting of hardwood, softwood and mixed forest (Northwest Territories, 2006) and ranging from very productive closed forest to open forest with stunted trees as the transitional forest-tundra ecotone is approached in the north/northeast. The dominant species include aspen and white and black spruces with jack pine and some balsam poplar also present.

With WATC set to 150m, the simulated total site biomass density is underestimated compared to reported values with all climate forcings (Figure 9). Forcing the model with the constant climate data set predicted the highest biomass density, whereas forcing with daily climate predicted the lowest. WATC set to 200 mm, total simulated biomass density increased and the differences among the three different climate data sets declined. However, these totals still fell short of the reported values obtained from the CanFI database (Lowe *et al.*, 1994). The proportion of hardwood to softwood biomass density was generally represented well with daily and monthly climate data but the hardwood component was underestimated when the model was forced with the constant climate data set (Figure 10 and Appendix 3).

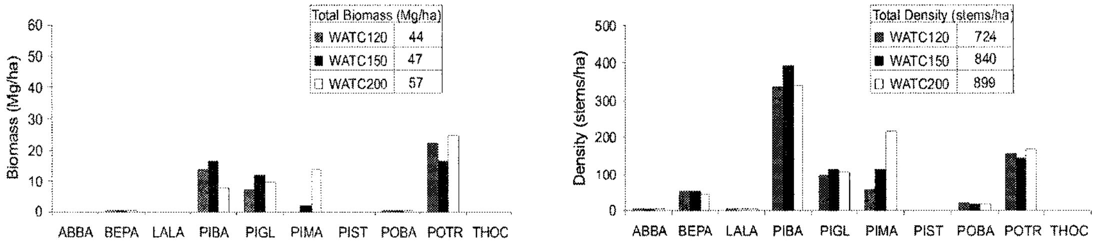
The dominant species were all represented in simulations forced by each of the three climate data sets, although the stem density of jack pine was higher, and that of black spruce lower, than expected when forced by daily and monthly climate. Conversely, black spruce was overly abundant in simulations forced by constant climate. Balsam poplar did not appear significantly in any of the simulations (Figure 14).

Simulations with the daily and monthly climate were both sensitive to WATC. There is little difference between the results simulated with these two climate data sets at WATC 150 and 200. With WATC reduced to 120 mm, both forcings predict an aspen-pine dominated forest, with the daily climate predicting higher jack pine biomass density and the monthly climate more aspen. Simulations forced by constant climate showed no sensitivity to WATC.

a) Daily Climate



b) Monthly Mean Climate



c) Constant Climate

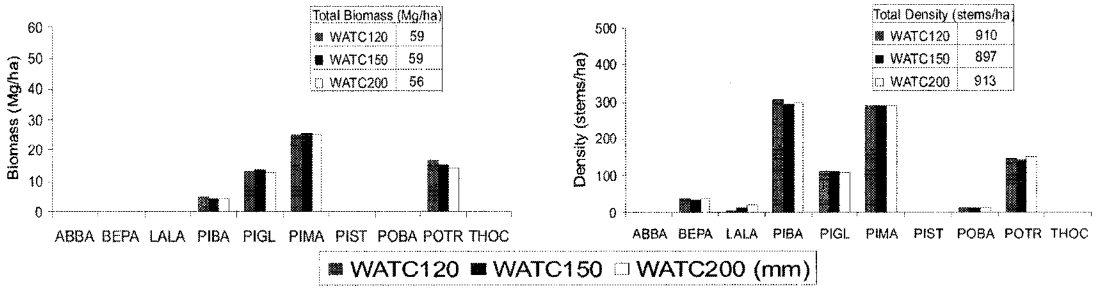


Figure 14. Simulated species biomass and stem densities for Fort Smith with FORSKA-2V+ forced with (a) daily, (b) monthly mean and (c) constant climate input data with WATC from left to right of 120 (gray), 150 (black) and 200 (white) mm. Reference WATC is 150mm. Species abbreviations: *Abies balsamea* (ABBA), *Betula papyrifera* (BEPA), *Larix laricina* (LALA), *Picea glauca* (PIGL), *Picea mariana* (PIMA), *Pinus banksiana* (PIBA), *Pinus strobus* (PIST), *Populus balsamifera* (POBA), *Populus tremuloides* (POTR), and *Thuja occidentalis* (THOC).

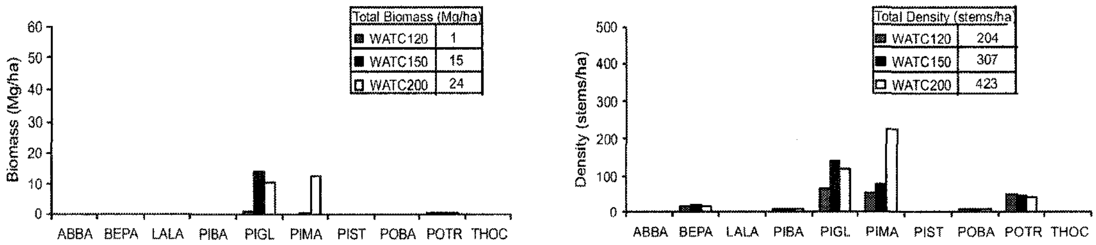
6.3.5 Treeline Site: Ennadai Lake

Ennadai Lake is located in the boreal forest-tundra ecotone. Forest vegetation in the Ennadai Lake region consists primarily of black spruce, with some larch and birch. White spruce can be found on hilltops (Larsen, 1965).

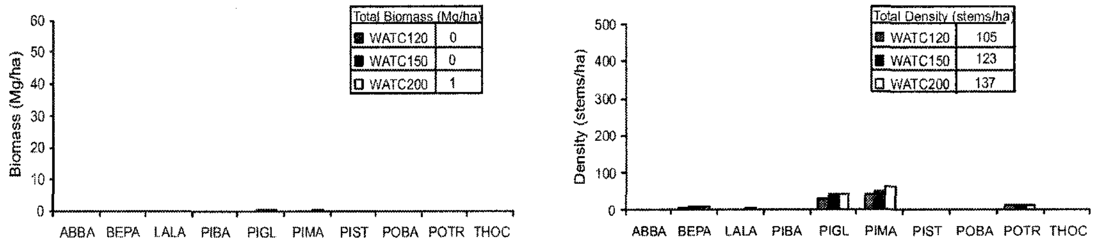
When FORSKA-2V+ was forced with the daily climate data, simulated total biomass density agreed closely with expected values (Figure 9). The predicted forest was dominated almost exclusively by spruces (Figure 15). With WATC set to 150 mm, black and white spruce were simulated to have similar stem density but black spruce biomass density was much lower. When WATC was increased to 200 mm, black spruce dominated white spruce in both biomass and stem density.

With the constant climate forcing, total simulated site biomass density exceeded expected values for all values of WATC. The proportion of hardwood was high, with aspen overly prevalent. Black spruce was abundant and dominated the simulated site biomass and stand densities but responded little to changes in WATC.

a) Daily Climate



b) Monthly Mean Climate



c) Constant Climate

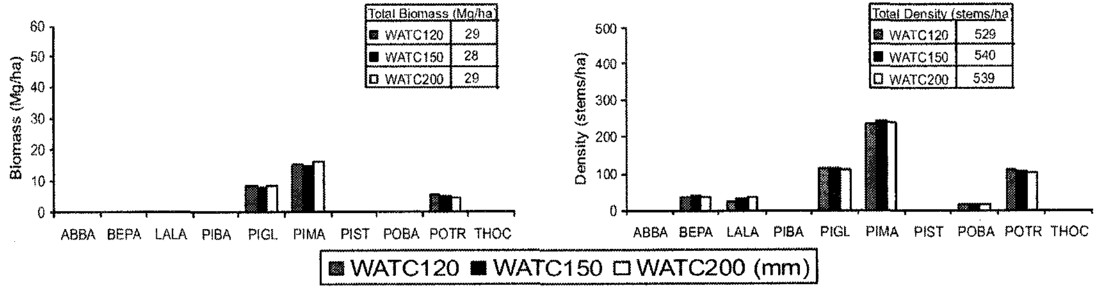


Figure 15. Simulated species biomass and stem densities for Ennadai Lake with FORSKA-2V+ forced with (a) daily, (b) monthly mean and (c) constant climate input data with WATC from left to right of 120 (gray), 150 (black) and 200 (white) mm. Reference WATC is 150mm. Species abbreviations: *Abies balsamea* (ABBA), *Betula papyrifera* (BEPA), *Larix laricina* (LALA), *Picea glauca* (PIGL), *Picea mariana* (PIMA), *Pinus banksiana* (PIBA), *Pinus strobus* (PIST), *Populus balsamifera* (POBA), *Populus tremuloides* (POTR), and *Thuja occidentalis* (THOC).

When the model was forced with monthly climate data, simulated biomass and stem densities were negligible at all levels of WATC (section 6.1 *The effects of daily temperature on growing degree days (GDD)*).

The influence of variable precipitation and temperature on the modeled results at this site was examined in more detail. In addition to the simulations with the daily and constant climate, drought indices derived from the daily climate record were used to "impose" variability in precipitation on the constant climate record (all other environmental factors remaining unchanged); similarly drought indices derived from the constant climate record were imposed on the daily climate data to combine constant precipitation with the effects of variable daily temperatures (all simulations assumed WATC of 150 mm), yielding four sets of simulations (Table 7, simulation results not shown).

Table 7. The four combinations of climate forcing used to examine the influence of variable precipitation and temperature on the modeled results at Ennadai Lake. Simulations are with reference WATC of 150 mm.

	Constant Temperature	Variable Temperature
Constant Precipitation	(1) constant climate forcing	(2) daily climate forcing with constant climate drought indices
Variable Precipitation	(3) constant climate forcing with daily climate drought indices	(4) daily climate forcing

(1) to (2): To test the influence of variability in temperature on the simulated results, the constant climate forcing (constant temperature, constant precipitation) was compared to the daily climate forcing combined with the constant climate drought indices (variable temperature, constant precipitation). The addition of temperature variability had little effect on white or black spruce but reduced the biomass and abundance of hardwoods, particularly aspen.

(3) to (4): The constant climate combined with the daily climate drought indices (constant temperature, variable precipitation) was compared to the daily climate forcing (variable

temperature, variable precipitation). Variable precipitation alone was not sufficient to exclude hardwoods from the species mix, and in fact, hardwoods made up almost half of the total species biomass and stem densities. It was only when the temperature became variable that hardwoods were excluded. Further, when precipitation was also variable, temperature variability had an even larger (negative) impact on the abundance of hardwoods.

(1) to (3): To test the influence of variability in precipitation, the constant climate forcing (constant temperature, constant precipitation) was compared to the constant climate combined with the daily climate drought indices (constant temperature, variable precipitation). When temperatures remained constant and precipitation variability increased, there was a small increase in white spruce combined with major reductions in black spruce and larch. When temperatures were constant, aspen and other hardwoods responded favorably to variable precipitation.

(2) to (4): The daily climate forcing combined with the constant climate drought indices (variable temperature, constant precipitation) was compared to the daily climate forcing (variable temperature, variable precipitation). In this case, variable temperatures had already excluded hardwoods (and larch) from the species assemblage. The remaining species were sensitive to the increasing variability in precipitation. The biomass and stem densities of black spruce were strongly negatively affected and white spruce was slightly favored. For white spruce, this increase was similar to when the temperature remained constant and precipitation varied. Thus, whether temperature was variable or not made little difference to the sensitivity of spruces to variable precipitation. It was also found that changes in precipitation had a larger effect on total simulated biomass density than changes in temperature.

6.3.6 Aspen parkland site: Rosthern

Rosthern is located just south of the southern limit of the boreal forest and the natural range of jack pine. Trembling aspen is the prevalent species in this region and conifers rarely occur naturally (Hogg, 1994). Just within the southern forest limit, it is still too dry for widespread natural regeneration of white spruce (Hogg, 1994; Bugmann *et al.*, 2001). However, some white spruce occur naturally along river valleys extending south into the parkland and prairies (Hogg and Schwarz, 1997; MacDonald, 2003).

All climate input data simulate a large proportion of jack pine which does not occur naturally in the area. The constant climate predicts a black spruce dominated forest for the region, including other species such as eastern white cedar which in reality are not present. Total biomass density simulated with the daily climate record and with WATC set to the reference level of 120 mm is high (50Mg/ha) but agrees more closely with the measured average in the area (Hogg, 1999) than simulations with the monthly and constant climate which highly overestimate it (107 and 85 Mg/ha, respectively) (Figure 9).

When forced by the daily climate data, FORSKA-2V+ predicts biomass density of aspen at the site quite accurately (29 Mg/ha), while the monthly climate overestimates it (76 Mg/ha) (Figure 16). Notably, and consistent with observations, when the model is forced with the daily and monthly climate data a higher proportion of hardwood species (predominantly aspen) is simulated at this site than any of the other study sites (Figure 10). Whereas at other sites jack pine and aspen increase relative to other species on soils of very low WATC, forced with the daily climate at this site even aspen are excluded on such soils. Observations support that at this site drought stress at low levels of WATC is severe enough to limit even the drought tolerant species (Hogg, 1994; Hogg and Schwarz, 1997). Simulations forced by daily and monthly climate data sets suggested that white spruce can survive at the Rosthern site, but only if soils are sufficiently deep to increase soil moisture availability to 200mm (Appendix 3).

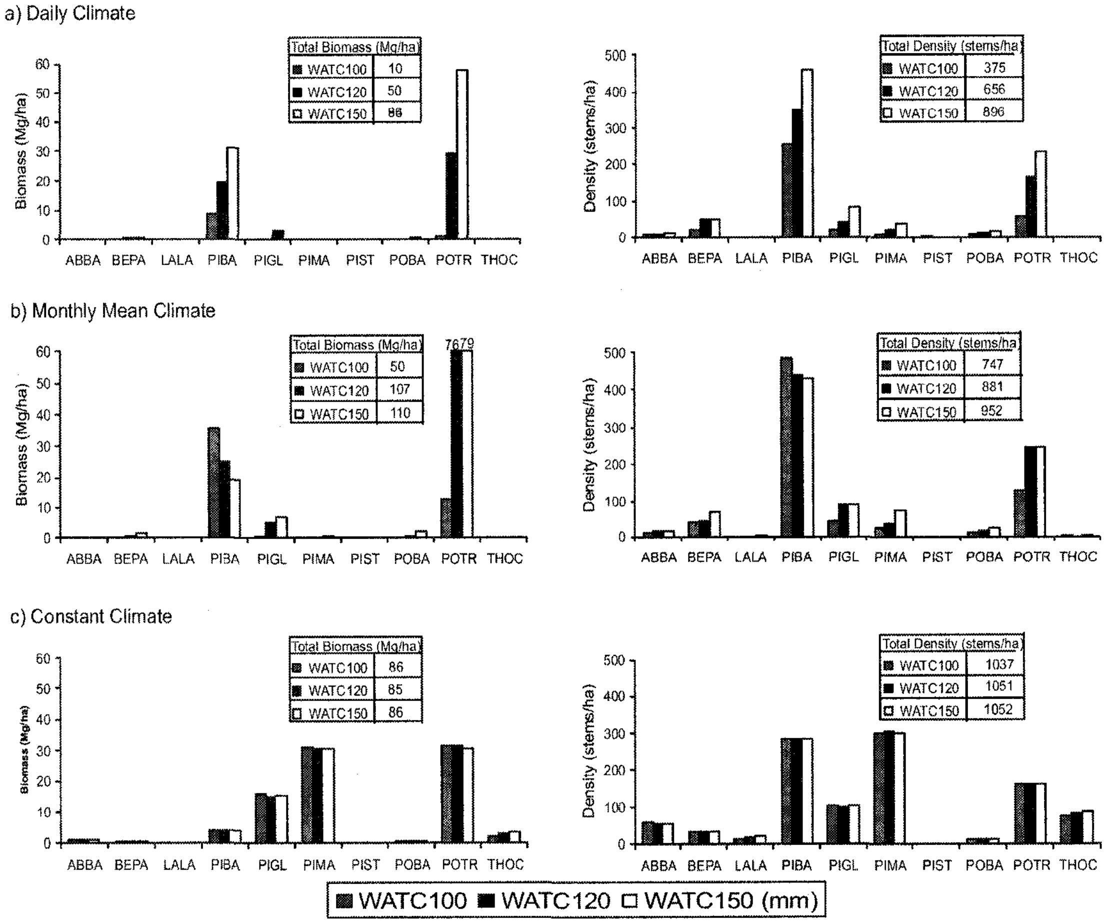


Figure 16. Simulated species biomass and stem densities for Rosthern with FORSKA-2V+ forced with (a) daily, (b) monthly mean and (c) constant climate input data with WATC from left to right of 100 (gray), 120 (black) and 150 (white) mm. Reference WATC is 120 mm. Species abbreviations: *Abies balsamea* (ABBA), *Betula papyrifera* (BEPA), *Larix laricina* (LALA), *Picea glauca* (PIGL), *Picea mariana* (PIMA), *Pinus banksiana* (PIBA), *Pinus strobus* (PIST), *Populus balsamifera* (POBA), *Populus tremuloides* (POTR), and *Thuja occidentalis* (THOC).

6.3.7. Tundra Site: Baker Lake

No trees were simulated at the Baker Lake site under any forcing scenario, in agreement with the treeless shrub tundra that is characteristic of this site.

6.4 Sensitivity testing of model processes and species parameters

The previous section documents the response of FORSKA-2V+ to forcing with climate data of different temporal resolution (daily, monthly and multi-year averages), for a range of plausible soil water holding capacities, at a wide range of sites with different bioclimatic characteristics and provided the basis for a rigorous assessment of model's behavior. A number of key issues concerning the general behavior of the model are investigated here in order to more fully understand the modeled responses.

6.4.1 Soil Water Balance: Snow and Frozen Soil

At both Flin Flon and Fort Smith simulated site biomass is underestimated regardless of the resolution of climate input data used. Associated with this, there is less simulated black spruce at Flin Flon than at Waskesiu Lake while field observations indicate that black spruce should increase in abundance along the transect from Waskesiu Lake to Flin Flon to Thompson. Fort Smith is located at higher elevation, on more sandy, well-drained soils than the surrounding area and there is therefore more jack pine. However, even with these local conditions taken into account, simulated jack pine is higher and simulated spruce lower than is realistic.

The simulated maximum drought indices at these two sites are also more severe than at all other sites except for the aspen parkland site (Rosthern) and are severe regardless of whether daily or monthly climate data is used (Figure 5). This simulation of frequent severe droughts was found to be a main control on the low simulated site biomass at the two sites. Sensitivity tests (which reduced all extreme annual drought indices to within only two standard deviations of the mean) resulted in a substantial increase in stand biomass from 43 to 66Mg/ha and from 49 to 71Mg/ha at Flin Flon and Fort Smith respectively (daily climate, reference WATC).

The timing and not the total amount of precipitation likely explains the deficits simulated at Flin Flon and Fort Smith compared to other sites. Flin Flon and Fort Smith were found to get a large fraction of annual precipitation in winter and/or have a low precipitation in the spring. The deficits simulated here are likely avoided in reality by the spring melt of accumulated snow (and its interaction with frozen soil) —a process which is not captured in the model.

The mean annual temperature and average total annual precipitation at Flin Flon (437mm) is similar to that of the adjacent site Waskesiu Lake (453mm). Accordingly, the modeled annual P-PET index, an index of climate moisture derived where positive values indicate a surplus of precipitation over evaporative demand (Hogg (1994), at Flin Flon and Waskesiu were comparable. Both were between 6 and 9 with only slightly higher (wetter) values for Waskesiu. Despite these similarities, the model simulates extreme drought events at Flin Flon that are more than twice the magnitude of those at Waskesiu Lake (Figure 5).

A closer assessment of the annual cycle of precipitation input indicates a difference in the seasonal timing of precipitation at theses two sites. Waskesiu Lake tends to receive more precipitation in the spring and summer months, whereas Flin Flon receives more precipitation in the late summer and fall (Figure 17). This also affects the seasonal timing of soil water availability. Comparing the most severe simulated drought year for Flin Flon (not shown), which is not a drought year for Waskesiu Lake, it was seen that although the annual P-PET index for the two sites is similar (6.8 and 8.1, respectively), three are considerable differences when the index is broken down by season. Flin Flon has more moisture than Waskesiu during the growing season from June to August (P-PET of 4.9 and 0.4 respectively) but much higher deficits during the spring months from March to May (P-PET of -9.2 and +0.6, respectively).

All five of the years with the highest simulated drought index at Flin Flon are characterized by lower than average springtime precipitation (in April and May) often resulting in soil water deficits early in the year. The deficits occur primarily in years when total annual precipitation is lower than average (Figure 18, year 33), but they can

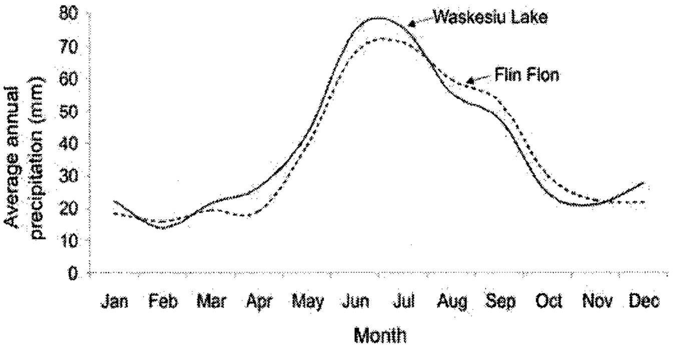


Figure 17. Long-term average annual total precipitation for Flin Flon (dotted line) and Waskesiu Lake (straight line).

also occur in years with above average precipitation. In year 68 of the simulation (Figure 18), Waskesiu Lake and Flin Flon both received above average amounts of total annual precipitation but the impact of low soil moisture in the spring caused a drought year to be simulated for Flin Flon.

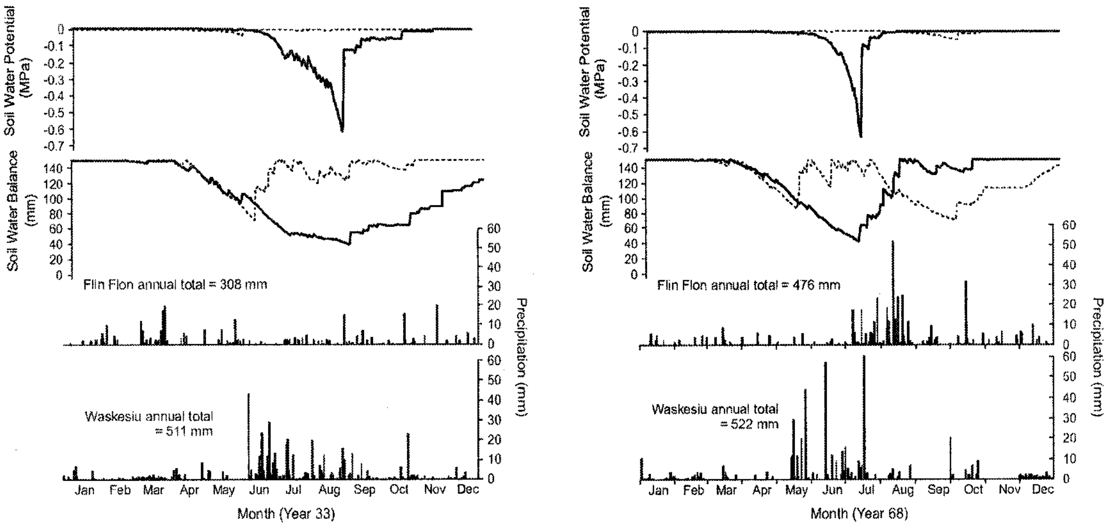


Figure 18. Soil water potential, daily soil water balance, and annual precipitation for year 33 (left) and year 68 (right), the two most severe simulated drought years for Flin Flon (continuous line) compared to the same years at Waskesiu Lake (dotted line).

The climate at Fort Smith is relatively cool with a long term annual average precipitation of 347mm (with considerable interannual variability). On average, Fort Smith receives approximately 65 mm less precipitation per year than does Rosthern, with a recorded minimum of 220 mm. However, the Fort Smith area does not have the severity of dryness experienced at Rosthern or other grassland/parkland sites (Hogg, 1994). At higher latitudes, cooler temperatures that result in lower evapotranspiration will offset the effects of lower precipitation on vegetation. Simulated PET and AET values at Fort Smith are indeed much lower than that at Rosthern. However, the lower evapotranspiration rate is not sufficient to prevent simulated severe soil water deficits. At WATC 120 mm the drought index is higher for Fort Smith than for Rosthern (Figure 5).

Four of the five years with the highest simulated drought index occur when total annual precipitation is only slightly below, or even considerably above, average. These years are characterized by a significant fraction of annual precipitation that falls as snow and/or low rainfall in the spring and early summer resulting in soil water deficits early in the year (Figure 19).

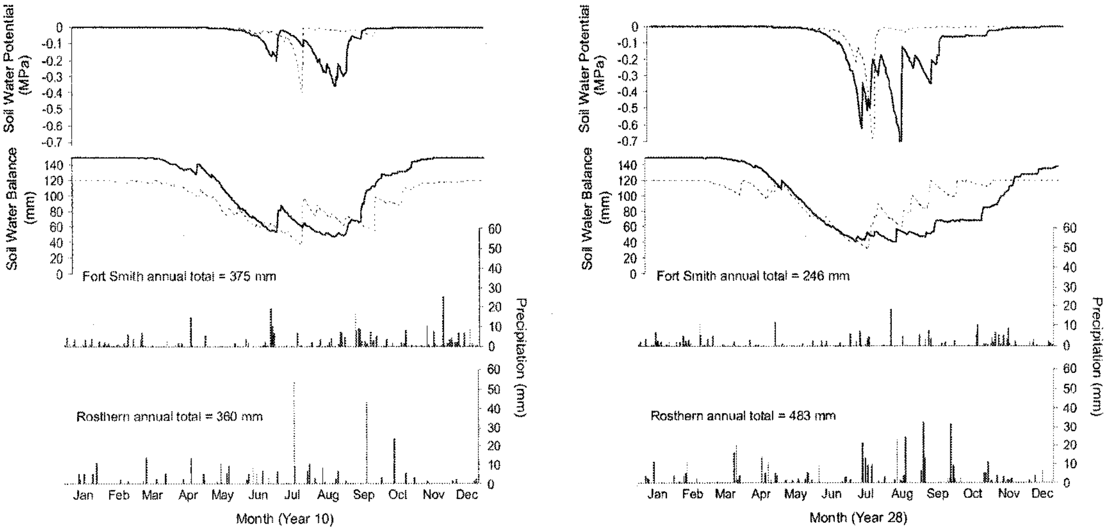


Figure 19. Soil water potential, daily soil water balance, and annual precipitation for two of the most severe simulated drought years, years 10 and 28, at Fort Smith (continuous line) compared to the same years at Rosthern (dotted line).

In FORSKA-2V's environmental sub-model, only the snow needed to fill the soil water bucket "accumulates". Any additional precipitation that falls as snow above WATC, a proportion of which would otherwise accumulate and be available in the spring, is lost to the system. Further, frozen soil can result in the presence of snowmelt retained at the soil surface in the spring or the accumulation of moisture in the active layer during the growing season due to poor drainage. These can have important effects on the presence and growth of vegetation, particularly black spruce (Larsen, 1965; Fowells and Means, 1990). Flin Flon receives a higher proportion of its precipitation in the winter than does Waskesiu Lake. At Flin Flon, on average over 90 mm of precipitation are simulated to "run off" each year, almost exclusively in the winter months. In year 33 (Figure 18), over 130 mm of precipitation in the preceding winter (Nov-Mar) were simulated as runoff and were therefore unavailable during the simulated growing season. In year 68, 94 mm were lost as runoff. As currently modeled, at Fort Smith approximately 110 mm of total precipitation is lost as "runoff" annually, almost entirely during the winter months. In years 10 and 28 referred to above, 154 and 90 mm of winter precipitation (Nov-Mar) was lost as runoff, respectively.

The simulations for Ennadai Lake may also be affected because a significant amount of precipitation is received in the winter. At Ennadai Lake, where average annual precipitation is about 360 mm, over 100 mm was lost as simulated run off each year. It was found that WATC needed to be set to at least 150 mm for the model to simulate a realistic abundance of black spruce. At Ennadai Lake, white spruce is observed on hilltops and black spruce on the lower slopes and valleys (Larsen, 1965) where permafrost tends to form and pooling occurs (Chapin *et al.*, 2006). The absence of frozen soil in the model can also be a factor in the lower simulated abundance of black spruce compared to white spruce on some soil types at this site.

6.4.2 Jack pine in the Parkland

In the aspen parkland ecozone, where aspen is the dominant species and the natural occurrence of conifers is very limited, an abundance of simulated jack pine required further investigation.

Jack pine is a drought tolerant species and it is common to see it on dry sites where other species are unable to persist (Blake and Li, 2003). The model indicates that if seeds are available and seedlings are able to survive the dry climate, the parkland region can support jack pine. Yet, jack pine is absent from this landscape.

Although the fire regime in the parkland may have played an important role to prevent jack pine establishment and expansion in the region (Curtis, 1959; White, 1983; Hogg, 1994) Hart, 1998; Johnson, 2008, the impact of severe drought on seedling establishment and survival is also thought to be an important factor excluding jack pine from the region (Hogg, 1994; Hogg and Schwarz, 1997; Hogg, 1999). When simulations were run with the most severe drought years removed from the climate record there was a large increase in jack pine, demonstrating the important impact that droughts common to this area have on this species. However, although jack pine does not occur naturally in the parkland, jack pine that has been planted in the area has survived well and indicates that moisture conditions do not exclude mature jack pine from this ecotone (Hogg, 1994).

In FORSKA-2V, the success of species regeneration is modified by the same drought tolerances that limit the growth of mature individuals (Table 2) despite the fact that the germination, growth and survival of seedlings can be more susceptible to drought than mature trees (Daniel *et al.*, 1979; Hogg and Schwarz, 1997; Price and et al, 2001; MacDonald, 2003). A reduction in the drought tolerance parameter of jack pine (from 0.53 to 0.38) was sufficient to reduce simulated jack pine biomass by approximately 30% but had little effect on its establishment, even though drought sufficient to reduce growth of mature individuals should theoretically also reduce the chances of survival of the more vulnerable seedlings. Drought tolerance as parameterized in the model is likely not sufficient to adequately differentiate between the tolerance of seedlings versus that of mature individuals.

6.4.3 Establishment

The model simulated unrealistically low total stand densities for all sites in this study, a shortcoming of FORSKA2 also highlighted in other studies (Bugmann *et al.*, 2001; Nalder, 2002). Stand densities in this study averaged approximately 1000 stems/ha for the central sites with lower densities at the ecotones. BOREAS field data of stands over 70 years of age indicates an average of 4000 stems/ha for Thompson and 2770 stems/ha for Waskesiu with decreasing densities towards the southern boreal forest limit. Younger stands could have much higher densities. Field data for stands with an average age of 90 years at Fort Smith, which likely includes even those stems smaller than 1 cm at breast height, indicates 7000 stems/ha on average.

Bugmann *et al.* (2001) suggests that the low simulated stem density is because FORSKA2 does not consider stems below 1 cm DBH and as a result the stand density totals are missing many small stems which may make up a large proportion of the stem count on observed plots. However, it is argued here that the low simulated stand density could and should be addressed through modifications to 1) the FORKSA process for vegetative reproduction (sprouting), and 2) to the prescribed species' establishment rate parameters.

1) Vegetative Reproduction

Sprouting is a major reproductive strategy in many broadleaved tree species, particularly in species such as aspen and balsam poplar, and even some conifers reproduce vegetatively by layering (Peterson and Peterson, 1992). In FORSKA2, if the diameter of a dead tree exceeds a certain species-specific minimum (SMN), and if adequate light is available at the forest floor, a random number of sprouts is established (but limited to a pre-determined maximum per year) for each species (SPT) as a function of the growth efficiency of the tree at "death" (DGE). Disturbance events are considered to remove the aboveground portions of all trees in a plot, but the stumps and belowground portions of species that can sprout are considered able to survive for several years. What is termed "dead tree" growth efficiency in this case is actually the growth efficiency of the live tree at the time of disturbance.

Although aspen reproduces by wind-borne seeds more in the boreal than in other parts of its natural range (Peterson and Peterson, 1992), at more marginal sites such as Rosthern, vegetative reproduction should give aspen an important advantage, because a well-established root system allows suckers to withstand drought better than seedlings (Hogg and Hurdle, 1995; Bond and Midgley, 2001). With the daily climate as input, the total simulated biomass density of aspen matches observations for this site quite well, however, even with the modification to the sprouting algorithm (section 5) the stem density of aspen is low and there is little simulated sprouting at this or any other site. At both Rosthern, a drought-prone site with low productivity and where only aspen occurs naturally, and Waskesiu Lake, a highly productive site where many boreal species are present, the simulations allow less than 1% of dead trees to produce sprouts – unrealistically low given the "vigorous" sprouting expected of poplars in general (Burns and Honkala, 1990a; Seymour, 1995).

The factors influencing the simulated establishment of aspen, both sprouting (the diameter requirement, sprouting rate, and "dead" trees growth efficiency) and seeding, were therefore examined at these two contrasting sites.

Sprouting

Diameter Requirement: Previous applications of the model have prescribed a diameter requirement of 15cm before aspen sprouting is enabled. However, aspen in the parkland is often stunted (shorter and with smaller basal area) compared to its growth in other parts of the boreal (Hogg and Hurdle, 1995). Further, even small, young aspen seedlings of 1 year of age, of presumably small diameter, are reportedly already capable of reproducing by root sprouts (Burns and Honkala, 1990a; Peterson and Peterson, 1992). Simulation output shows that a large number of "dead trees" are not considered for sprouting because they have not reached the required diameter. At Rosthern, approximately 25% of "dead" aspen meet the diameter requirement to be considered for sprouting in the model. 42% meet the requirement at Waskesiu Lake. The low number of simulated sprouts could therefore be due to an unrealistic minimum diameter requirement in the model. It should be noted that the parameterization for SMN adopted from Price *et al.* (1996) was taken directly from European aspen, *P. tremula*, and this may not be appropriate size for its boreal counterpart, *P. tremuloides.*

With SMN for aspen reduced from 15cm to 10cm, almost twice as many (40%) "dead" aspen at Rosthern achieved the required diameter and simulated sprouting increased five-fold. At Waskesiu Lake, 54% of "dead trees" met the minimum diameter requirement and sprouting increased seven-fold. However, these increases represent only a small increase in absolute numbers of sprouts per year and at both sites they had little effect on aspen's simulated long-term success (biomass and stem densities) (Appendix 4).

Sprouting Rate: A mature aspen root system can produce tens of thousands of sprouts per hectare (Peterson and Peterson, 1992; Johnson, 2008). Even though many of these may not survive to the notional size of establishment assumed in FORSKA-2V (1.3 m height with 1 cm diameter), this observation strongly suggests the potential sprouting rate as parameterized in the model (at three sprouts per aspen individual in a 0.1 hectare plot) must be considered extremely conservative. With a comparatively small increase to the current maximum potential from 3 to 6 sprouts per individual, aspen sprouting tripled at Rosthern and there was a five-fold increase at Waskesiu Lake. At both sites, the increase in sprouting was less than that obtained by reducing the minimum diameter requirement but the impact on site biomass and stem densities was greater suggesting that sprouts from larger trees are more apt to survive and grow. This is consistent with the principles of forest gap dynamics - larger diameter trees leave a larger canopy gap and, in the case of trees which can reproduce vegetatively from stumps, larger live root systems that can better support the growth of the new sprouts. Further increases to the sprouting rate were found to have even greater effects on the sprouting activity and the biomass and stem densities of aspen.

"Dead Tree" Growth Efficiency: In the model, tree growth efficiency at the time of simulated death, DGE, determines how prolifically "dead" trees will sprout. In the simulations, of those trees that have sufficient diameter to be considered for sprouting

often no sprouts are established. To examine the sensitivity of simulated sprouting to calculated tree growth efficiency, the model was modified so that every dead aspen individual above the specified minimum diameter was permitted to establish the maximum number of sprouts (3) rather than a number reduced by the "dead" tree's growth efficiency. Overriding the growth efficiency requirement resulted in the greatest single increase in simulated site biomass and stand densities. At the Rosthern site, sprouting increased more than 11-fold, leading to increases in total aspen biomass and stem densities of 41% and 58%, respectively. At Waskesiu Lake, there was a 17-fold increase in sprouting and biomass and stand densities increased by 37% and 46%, respectively.

Combined, changes to minimum diameter requirement, sprouting rate and DGE controls have the potential to strongly affect the simulation of sprouting in the model. At Rosthern, a reduced diameter requirement increased aspen density by only 7%. If the growth efficiency constraints were also removed, stem density increased by 141% and biomass density by 98%. A reduced diameter requirement and increased sprouting rate combined increased stem density by 38% and biomass density by 20%. Together with growth efficiency constraints removed, stem density increased by 785% and biomass density by 295%. "Turning off" the tree growth efficiency (DGE) control permits all dead trees of sufficient diameter to produce the species-specific maximum number of sprouts and provides an additional indication of the simulated sprouting potential of poplars were the DGE control relaxed and sprouting rate increased. The analysis does not, however, assess whether the relationship between the simulated value of aspen's growth efficiency and the probability of sprouting in FORSKA2 is reasonable.

Establishment from seed vs. sprouting

In FORSKA2, sprouting is only considered as a reproductive strategy following an individual's death due to "intrinsic" mortality or following removal of all trees by disturbance. Currently, the fact that hardwoods also regenerate by sprouting as part of routine annual regeneration throughout their life-cycle is ignored (Peterson and Peterson, 1992; Seymour, 1995). Aspen therefore has less opportunity for regeneration during the "planting" of seedlings that occurs on a regular basis at each site.

Increasing aspen's seedling establishment rate (e.g., by 50 or 100%) can have a greater impact on biomass and stand densities at both Rosthern and Waskesiu Lake than the small increase to the simulated sprouting rates reported above, with slightly larger responses at Waskesiu Lake. Although simulated aspen also benefits from increased seedling establishment rate at Rosthern, establishment by sprouting alone should be a successful strategy given that, in reality, the number of aspen regenerating from seed is likely to be very small or even zero in this parkland. When species parameters are modified so that sprouting following death or disturbance is the primary regenerative strategy (aspen maximum sprouting rate was increased 10-fold to 30 and seed establishment rate reduced from a maximum of 15 to 1.5 saplings per year) the overall increase in simulated sprouting was large at Rosthern (factor of 48 increase) and long-term simulated aspen stem density and biomass density both increased. Conversely, despite a large increase in sprouting rates when the same modifications were applied at Waskesiu Lake, there was hardly any additional sprouting simulated and both the biomass and stem densities of aspen decreased to approximately half of what they were with the original seedling establishment and sprouting rates. In the absence of simulated competition from other species, however, aspen also sprouted prolifically at Waskesiu Lake.

2) Species' Establishment Rates

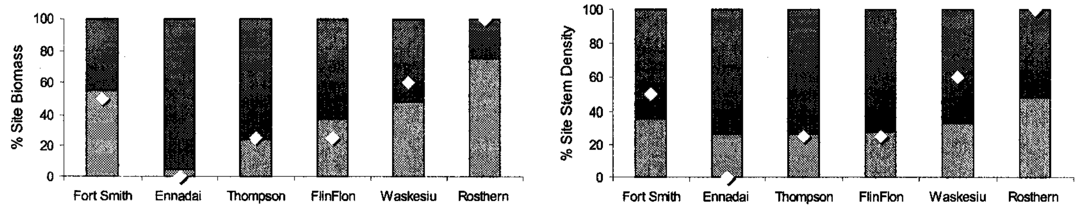
Plausible explanations for the high abundance of simulated jack pine in the parkland, such as the absence of species-specific seedling drought tolerances in the model, have been discussed. Yet, there is also a systematically high simulated stem density of jack pine compared to other species at all sites, for all levels of WATC, and for all climate data sets. Examination of the jack pine establishment rate relative to other species was therefore also warranted.

Many of the species establishment rates used in FORSKA-2V were taken from studies in Europe (Price et al. 1996, 1999a). In the North American boreal forest, the establishment rates of some species might be higher because of adaptation to relatively frequent and intense fires (Lindner *et al.*, 1996; Price *et al.*, 1999a). The modification to species' post-fire establishment rates introduced by Price (1999) (an increase in the regeneration rates of all species for the first year following disturbance by a factor of 50 and a doubling of the establishment rate of jack pine relative to the other species), were intended to introduce to the model the response of fire-adapted species to large-scale disturbance. The modifications were also applied to address the model's low simulation of stand stem density in the western Canadian boreal context. At Waskesiu Lake for instance, applying Price's (1999) modifications increased the spatially averaged stand stem density from 600 to 1000 stems/ha. However, according to the BOREAS project data (Halliwell and Apps, 1997), this is still less than half the stem density expected of even the older stands (above 70 years).

The modification made to FORSKA-2V+ in this study favors only the rapid post-fire establishment of the three most aggressive early pioneer species (jack pine, aspen and black spruce) and thereby differentiates the rapid establishment rate of jack pine from the other less aggressive (non-pioneering) species. Therefore, the increased annual establishment rate parameter prescribed for jack pine in Price (1999) may no longer be appropriate. Reverting to the earlier rate (10 as opposed to 20) improves the balance of jack pine abundance relative to other species in the species mix but also results in a large reduction of total stand stem density. Alternatively, given that the establishment rates of all species may be set to unrealistically low levels for the boreal forest rather than reduce the jack pine establishment rate parameter by one half to revert to its former value, it may be defensible to increase the establishment rates of the other species proportionately (i.e. double them). To test this hypothesis, the establishment rate of jack pine was left unchanged and that of all other species on the species list was doubled.

With this modification applied (and the model forced with the daily climate at reference level WATC for each site), at almost all sites the simulated biomass and stem densities of species increased in relation to jack pine. Along the transect, stand biomass density increased only by an average of 25% as climate and other environmental resources were not changed and at most sites a reduction in the biomass density of jack pine is merely redistributed to other species. However, total stand densities increased by 43%, or about 300 stems/ha, on average, a modest but not insubstantial increase (Appendix 3).

Establishment Rate Change



No Establishment Rate Change

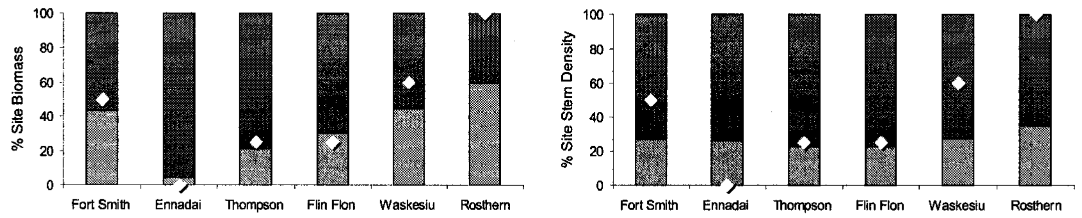


Figure 20. The ratio of simulated hardwood to softwood biomass (left) and stem (right) densities at each site along the transect with FORSKA-2V+ and species' establishment rates doubled (jack pine establishment rate held constant) (top panels) compared to simulations with FORSKA-2V+ before establishment rate changes (bottom panels). Markers (white diamonds) indicate observed values (see also Figure 9). Simulations are with FORSKA-2V+ forced with daily climate and with WATC set to the reference level at each site.

The simulated proportion of hardwood and softwood biomass density along the transect were further improved compared to observed levels (Figure 20). The proportion of hardwood and softwood stem density also improved compared to observations, but to a lesser extent. The model assumes that all species have seeds available at all locations and simulated stand stem densities, particularly at the ecotones, continue to be biased by the artificially high establishment of species that would otherwise be excluded by lack of seed availability or by environmental impacts on germination and seedling survival (Busing and Solomon, 2005) which are not currently considered in the model. For example, several species that are not actually present at Ennadai Lake are able to establish but do not grow and contribute little to simulated biomass density (Figure 15).

Notably, while the relative establishment rates for all species other than jack pine were not changed, the biomass and stem densities of some species increased more than others (Figure 21). Both the biomass and stem densities of black spruce increased comparatively more than the other species. There was a particularly large increase at Flin Flon, Fort Smith and Ennadai Lake. The increasing abundance of black spruce observed from Waskesiu to Flin Flon to Thompson, and at Ennadai Lake, was captured markedly better in the simulations (Appendix 5). A large increase in white spruce biomass density at Fort Smith made simulation results more consistent with observations at this site. The advantages that aspen (and other pioneer species) gain by establishing rapidly and in large numbers following a fire was now more apparent in the early succession.

It seems that higher (and arguably more realistic) establishment rates improved the representation of inter-specific competition in the model. Equally noteworthy is the observation that although the establishment rate of jack pine was not changed its simulated biomass density was substantially reduced. Jack pine stem density was also reduced not only relative to the other dominant species but also to its former values. The largest reductions occur for soils where WATC is set to 200 mm or higher. This non-linear impact on jack pine when other dominant species are permitted to "fairly" compete for initial establishment demonstrates the importance of competition among species- and the ability of FORSKA-2V+ to successfully capture these dynamics.

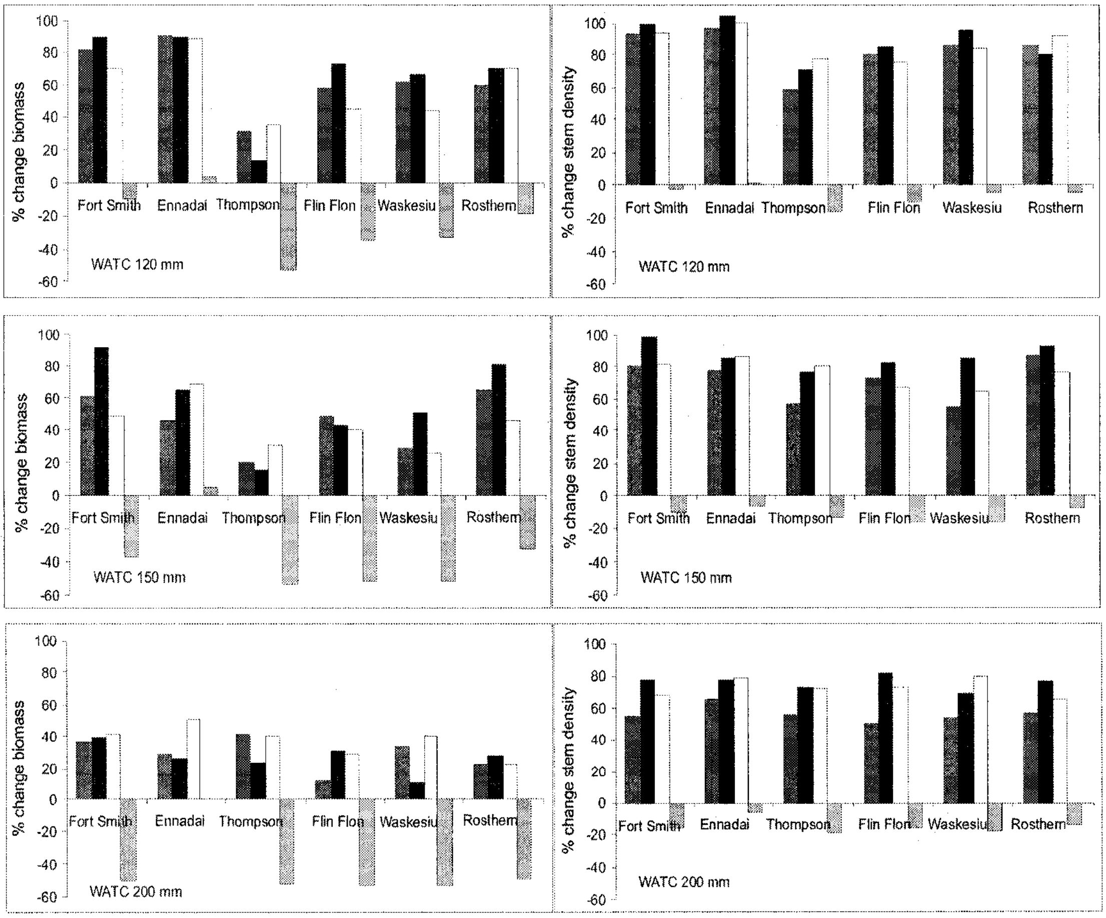


Figure 21. Percent change in simulated species biomass (right) and stem (left) densities with the doubling of species establishment rates (jack pine rate held constant). FORSKA-2V+ is forced with daily climate and WATC is set to 120, 150 and 200mm. Species from left to right: *P. glauca* (dark gray), *P. mariana* (black), *P. Tremuloides* (white) and *P. banksiana* (light gray).

7 DISCUSSION

The FORSKA2 model, and its derivative FORSKA-2V, was not originally designed for use with daily climate data. The simulated response of the model to the day-to-day variability and extremes associated with daily data were unknown for Canadian boreal forest. Nonetheless, a number of important ecophysiological processes are simulated on a daily time-step in FORSKA2 and this study has demonstrated that the modified FORSKA-2V+ model is strongly sensitivity to the choice of climate data resolution. A particularly important example documented here is that the effects of variations in daily temperature and precipitation on soil water balance, and the subsequent frequency and intensity of simulated drought events, are a major cause of differences in simulated output when daily input data are used in place of monthly mean or constant climate data.

Ecotone Sites

At sites where temperatures and/or moisture are limiting and as a consequence where species may be at the limits of their natural range, notably at ecotones, climate variability and extremes would be expected to have a strong influence on species survival and growth. Accordingly, simulations with the FORSKA-2V+ model were found to be particularly sensitive to the use of short-term climate variability at these sites (Rosthern in the south and Ennadai Lake in the north). Moreover, the most realistic simulated forest for these two sites was obtained when the model was forced with daily climate data.

At Rosthern, located at the transition between the boreal forest and the prairie, only forcing with daily data captured the moisture deficits and recurring droughts that are characteristic of the region. Simulations with daily climate data resulted in more realistic total site biomass and, with the exception of the presence of pine (for which there are plausible explanations—see next paragraph), more accurate predictions of species abundance and growth, especially on the drier soils. Simulations forced by monthly climate data were found to overestimate the observed aspen biomass quite significantly and the simulated behavior of pine (an increase in abundance with increasing drought stress) was implausible given the moisture constraints in this dry climatic region.

The model suggests, and field observations support, that under the present-day climate pine should be able to grow in the region around Rosthern if seedlings can establish successfully. This strongly suggests that the absence of jack pine in the aspen parkland is due to climate effects on conifer regeneration – effects that are not well represented in the model. Drought tolerance as parameterized in the model is likely insufficient to enable the model to simulate important environmental impacts on jack pine seedling germination, growth and survival. Additionally, this study has demonstrated that annual regeneration rates for jack pine in the absence of fire may be overestimated and that competition from aspen vegetative regeneration ("sprouting") is also not well represented in the model but has the potential to substantially reduce the presence of jack pine at Rosthern. These factors likely explain the unrealistic predominance of simulated jack pine compared to the actual landscape at Rosthern.

Similarly at Ennadai, located at the northern treeline, only simulations forced by daily data successfully simulated the climatic limits on stand biomass. Forcing the model with daily climate conditions proved most successful at simulating the exclusion of hardwood species from the site. It was found that only when the model is forced with daily precipitation data was the variability sufficient to simulate a realistic abundance of white and black spruce on soils with different water holding capacities. The need to set WATC to at least 150 mm for the model to simulate a realistic abundance of black spruce was likely attributable to the model's deficiency in accounting for the high fraction of frozen precipitation and the presence of frozen soil at this site. Although the northern treeline is considered to be primarily temperature limited, this study demonstrated that variable precipitation also has a strong influence on spruce and may have as large an effect on total biomass and species abundance and growth as temperature.

Growing degree days (GDD) are one means of characterizing the thermal environment important to plant growth. However, GDD were consistently underestimated at all sites when using monthly data. This study confirms that daily resolution climate data are needed to estimate GDD with acceptable accuracy. At species' northern range limits, where low mean annual temperatures result in short growing seasons and every degree day can make a difference to tree survival and growth, such underestimation was significant. At Ennadai Lake, (typical of northern sites), the underestimation of GDD from monthly data was particularly acute and caused the model to critically underestimate seedling survival and stand productivity. It is possible to correct GDD sums derived from monthly mean climate data, but this is a challenge because the magnitude of the underestimation varies by site and from year-to-year. Further, other impacts of daily climate variability, such as on the soil water balance, were found important for simulating realistic species composition and growth at Ennadai Lake. Therefore, the use of monthly mean climate data, even after correcting for GDD biases, is not recommended.

The use of the constant climate data as input to the model resulted in overestimation of total biomass density at both of the ecotone sites. The use of long-term averages prevents the model from simulating appropriate moisture constraints in the southern, dry aspen-parkland that exclude conifers from the Rosthern area. As a result, the simulated forest was unrealistically dominated by spruce with too low a proportion of hardwood. There was also a high simulated abundance of species not actually present in the region. At the northern ecotone, forcing the model with constant climate data failed to capture the low temperature extremes and resulted in too large a proportion of hardwood being simulated. It also failed to simulate the different soil moisture conditions that result from variations in soil water holding capacity and that greatly influence the presence of white versus black spruce in the Ennadai Lake region (Larsen, 1965).

Sites in the central boreal forest

Forcing the model with daily climate also improved the model's performance at sites in the central portion of the boreal forest, although there was less of a difference between the model's responses to daily and monthly mean climate when compared to those at the ecotone sites. Simulations with both the daily and monthly mean climate respond to variations in soil water holding capacity which is an important control on species distribution (Fowells and Means, 1990). The greatest difference between the modeled response to the daily and monthly mean climate occurred when soils were assumed to have a low water holding capacity (WATC set to 120 mm). However, the latter responses are difficult to validate without more detailed field observations of soil properties.

In general, the use of constant climate data reduced the realism of the simulated forest along the transect compared to simulations with the monthly or daily climate data. The only exception to this general rule was at Thompson, see below. The proportion of hardwood biomass was underestimated at most sites and species such as eastern white cedar that in reality are not present in the region were included in the simulated species assemblage. There was little or no sensitivity to variations in WATC at any of the modeled sites. In other words, simulations with a constant climate suppress the effects of soil moisture deficits on vegetation that occurs in nature, causing the model to fail to simulate realistic species' composition, abundance and growth.

At both Waskesiu and Thompson, simulated biomass density agreed with the observed values when the model was forced with any of the three climate records and at all levels of WATC, suggesting that climate variability is not a key control on total productivity at these sites. At Thompson, present-day climate variability also did not appear to be a critical factor for species-specific composition and growth, and the results for forcing with the daily, monthly mean and constant climate were very similar. Thompson has the highest and least variable precipitation of all the studied sites and the simulated results support that annual precipitation is generally high enough to prevent water deficits even on sites with relatively low water holding capacity, presenting conditions favorable to the success of black spruce. The model realistically predicted black spruce even when WATC was set to the lowest value. The proportion of hardwood species in the simulation were still underestimated but this deficiency could be eliminated by the proposed adjustments to species' seedling establishment rates.

On the contrary, at Waskesiu the interannual precipitation is highly variable and the simulated composition of species and their relative abundance and growth depended on the resolution of the climate forcing used and the soil water holding capacity assumed (value of WATC). The mixed forest predicted using the daily climate data (dominated by aspen, jack pine and spruce) varied realistically with changes in soil WATC. The results agree with observations that species that can tolerate high day-to-day variability in precipitation are favored at this site.

At other sites in the central boreal forest (Flin Flon and Fort Smith), the variable climate records reduced simulated total site productivity and had a strong effect on species-specific abundance and growth, again interacting with the assumed WATC at each site. The model responded in a realistic manner to simulated moisture limitations at Flin Flon and Fort Smith. As climate variability increased (i.e., from constant to monthly mean to daily climate), there was a reduction in the simulated abundance of black spruce. At higher levels of WATC, aspen increased. At lower levels of WATC, the biomass and stem densities of most species were reduced and there were greater amounts of pine, consistent with field observations. At Flin Flon, the assemblage of dominant species simulated using daily climate was reasonable, although in reality more black spruce and less jack pine are present. At Fort Smith both daily and monthly climate data caused the model to predict plausible aspen-pine forest with some black and white spruce, although compared to inventory data simulated spruce biomass and stem densities were low.

As mentioned (section 6.4.1), FORSKA-2V does not accumulate snowfall as frozen water, but instead allows it all to be lost as runoff once the WATC "bucket" is filled. Sensitivity analysis suggested that at sites such as Flin Flon and Fort Smith where a large fraction of annual precipitation typically falls during the winter and/or there is relatively little precipitation in the spring, the impacts of the spring melt of accumulated snow (and its interaction with frozen soil) could be substantial. At Flin Flon and Fort Smith, therefore, the model generally exaggerated the simulated soil water deficits compared to reality, which then contributed to simulated biomass density being underestimated at these sites. This result occurred regardless of the resolution of the climate record. This limitation of the model likely also contributed to the low simulated abundance of black spruce at both sites and its tendency to simulate pine-dominated "dry-climate" vegetation at Fort Smith.

To account for the fact that there may be a model bias towards simulating more severe soil moisture deficits than typically occur in reality, WATC at these sites was increased to "artificially" capture more of this winter runoff. Simulations at Flin Flon with WATC increased to 250 mm increased the abundance of black spruce and reduced the biomass and stem densities of aspen, which was more consistent with observations for this site. At Fort Smith, the increase of WATC to 250mm caused a large increase in the biomass of black and white spruce and a reduction in jack pine. Modification of species establishment rates (discussed below) were also found to improve the simulated proportions of the expected dominant species at these sites, including more black spruce at Flin Flon and more black and white spruce and less pine at Fort Smith.

A further explanation for limitations in the model's performance at Flin Flon and Fort Smith is that forests in these regions appear to have considerably more spatial variability in forest structure (height, biomass and stand stem density) than do forests in the vicinity of Waskesiu Lake and Thompson. Although simulated biomass density totals were compared to field observations and reported inventories, it must be recognized that there are likely to be limitations in the observed data which may make valid comparisons difficult. Forest inventories tend to focus on stands with commercial value and may be biased towards closed forest; often only the larger diameter classes are included in the inventory. One study (Haripriya, G.S., 2002) estimates that up to 30% of small diameter classes are omitted from stand inventories. In areas with considerable spatial variability, such as Flin Flon and Fort Smith, there is also strong possibility that reported inventories will be less than the spatially-averaged biomass simulated by FORSKA2 as an average for the landscape.

Future improvements to the model

The sensitivity analysis revealed several key issues which should be considered when assessing the simulation results and which can inform future improvements to the model processes and species' parameterization.

Soil Water Balance: Changing from constant climate to monthly or daily climate records increases the simulated intra-and inter-annual variability in soil moisture and leads to greater sensitivity to changes in WATC. These differences are captured in the yearly integrated drought indices derived from the three different climate data sets (Figure 5). Accurately capturing all precipitation available to the system is particularly important when forcing the model with daily data, and when applying the model to regions where the spring snowmelt comprises a significant portion of the annual hydrological budget. Including representation of frozen precipitation and winter surface hydrology in the model is therefore recommended.

At a minimum, it is important to modify the model to ensure that some fraction of winter "runoff" is made available in spring. For example, the JABOWA2 model accumulates precipitation as snow when air temperatures drop below 0 °C and melted water is released gradually when temperatures rise above freezing (Botkin and Nisbet, 1992). (The original JABOWA model, like FORSKA2, does not simulate soil temperatures.) A similar approach could be adopted in FORSKA-2V. In practice, it would require some site-level validation to obtain reasonably realistic additions of snow-pack moisture to the soil, given that in reality some of the annual snowfall sublimes or contributes to overland flow in early spring and is therefore unavailable to plants.

There is also a clear need for better data on the variability of soil types and particularly plant-available soil water holding capacity in Canada's forested regions. Of course given the vast areas concerned, these data needs are not likely to be resolved in the foreseeable future. In the meantime, it is important to continue to study model responses to climate variability for a range of plausible soil water holding capacities at each site.

Establishment: Earlier studies that applied FORSAK-2V to the Canadian boreal (Price *et al.*, 1999a; 1999b) adopted the regeneration parameters for comparable European species, making only minor modifications for post-disturbance conditions. They did not consider the possible need to modify regeneration processes and parameters for stand development of Canadian boreal species (D. T. Price pers. comm. 2008).

Sensitivity analysis identified a number of potential deficiencies in the model processes and parameters governing vegetative regeneration ("sprouting") that appear to be causing a systematic underestimation of sprouting in the model. Reasonable decreases in the minimum diameter limitation and increases in the maximum sprouting rate should be considered, which would both have a positive effect on simulated sprouting activity. The annual establishment of new saplings as a regular aspect of stand development (either vegetatively or from seed) is also critical to aspen's long-term success, particularly at sites where it faces competition from other species. Modifications should be made to the model to permit aspen and other hardwoods to utilize their vegetative reproductive strategy not only at death but throughout their life-cycle as a part of routine annual regeneration when conditions are favorable. Further, the current model formulation assigns the same initial diameter and leaf area to both seedlings and sprouts, but modification may also be warranted to reflect that saplings can grow from sprouts relatively quickly and can out-compete other species which must regenerate from seed (Peterson and Peterson, 1992; Mitton and Grant, 1996).

Increasing the establishment rates of species to more realistic levels was found to: increase total simulated stem densities (closer to observed values), reduce the overabundance and growth of pine that had been simulated at some sites, increase the proportion of hardwood in the species mix, and improve the establishment and long-term success of black spruce. Adjusting species' seedling establishment rates may therefore reduce a number of deficiencies in the simulated outputs but requires careful examination in conjunction with the interacting factors that influence hardwood vegetative regeneration.

Use of the model to study future climate change

Many climate models predict an increase in total precipitation across temperate North America but droughts are also likely to increase in the continental interior due to increasing evaporative demand associated with rising temperatures (IPCC, 2007b). Changes in the seasonal cycle of precipitation are also predicted by some climate models. The use of daily data improved the model's ability to simulate seasonal variations in soil water balance, including soil moisture limitations. This makes it a valuable tool for assessing future impacts of climate change on the boreal forest where changes in water availability are predicted to be an important determinant of forest response to a warming climate (Bates *et al.*, 2008). The proposed modification to the model's representation of frozen precipitation and winter surface hydrology should improve its ability to account for plant-available soil moisture in the system during all seasons.

In the Canadian boreal forest, stand replacing fires are a major control on forest structure and succession, and their frequency is projected to increase in association with global climate change (e.g. Flannigan 2008). It will be critically important to consider the associated impacts of climate change on the natural disturbance regime (i.e., including outbreaks of insect attacks and diseases as well as fire) in assessing climate change impacts on Canada's forests. Although disturbances were not a focus of this study, the stand development effects of disturbance by fire are represented well in the model. Therefore, FORSKA-2V+ can support assessment of both the direct impacts of climate change and of related changes to disturbance frequency.

Sprouting is an important regeneration strategy which may facilitate a shift towards greater aspen composition in the boreal forests in increasingly dry areas (Hogg and Hurdle, 1995) and/or where fire becomes too frequent for successful seed regeneration of some conifers (Price, *et al.,* (2001). Modifications proposed in this study to more adequately represent this reproductive strategy will improve the model's projections of the future behavior of aspen, including its role in stand regeneration following fire.

Finally, the southern/northern ecotones are widely considered to be moisture/temperature limited and where species ranges are most sensitive to changes in precipitation/temperature associated with future climate warming (IPCC, 2007a). Forced with daily data, the model seems well-suited for assessing the impacts of future change in climate and climate variability on ecotones.

8 CONCLUSIONS

This study compared boreal forest development as simulated by a modified version of the FORSKA2 model (FORSKA-2V+) at several sites along a broad north-south bioclimatic gradient in central Canada. The model proved to be sensitive to the choice of climate data resolution. The study established that using daily climate data to drive FORSKA-2V+ results in significant improvements in simulated forest characteristics, as compared to monthly mean or constant (long-term averaged) climate data, thereby confirming the hypothesis that forcing the model with daily resolution climate data would improve its performance. The use of daily climate data improved the model's skill in predicting large scale differences in forest structure at a broad range of sites with different climatic regimes, including the ability to simulate the transition from boreal forest to aspen parkland in the south and from boreal forest to forest-tundra and tundra in the north. Only simulations forced with the daily data provided realistic results for the northern and southern ecotone sites. Forcing the model with daily data also improved predictions of species-specific abundance and growth at most sites along the transect. Therefore, the use of daily climate data was found to improve both the accuracy and the generality of the model.

Modifications were introduced to species' post-fire regeneration rates to satisfactorily simulate the rapid colonization of sites by post-fire pioneers such as aspen, jack pine and black spruce, which improved the realism of species succession. Sensitivity testing identified other priority areas where adjustment to model processes and species' parameters can further improve model performance.

These priority areas include improvement to the representation of hardwood vegetative regeneration during regular stand development (i.e., not only for recolonization of sites following disturbance). Adjusting the sprouting rates of hardwood species and the establishment rates of all species to more realistic levels was shown to be an effective approach to raise the total stand stem densities, increase the abundance of aspen particularly early in succession, reduce the abundance of pine, and enhance the simulation of inter-species competition, particularly the long-term success of black spruce. Including the representation of frozen precipitation and winter surface hydrology is a also key aspect that is needed to ensure that winter snowfall is treated as a source of water available to plants in the spring.

Several researchers have proposed that more physiologically-based processes and parameters are needed to enable forest gap models to simulate effects of climate variability and change more successfully. This study supports the conclusion of Price *et al.* (2001) that better representation of the physiological requirements of species' regeneration processes is needed and recommends that efforts be focused on the development of better representations of the effects of drought on hardwood sprouting and of drought tolerances for seed germination, and seedling survival and growth of all species.

In summary, the findings of this study support the hypothesis that climate variability and extremes are important factors in boreal ecosystems. Failure to consider changes in climate variability and to use more detailed climatic variables in the assessment of the impact of future climate change on the boreal forest may be limiting the predictive capabilities of the models and could result in over- or under-estimation of changes and reduced capacity to identify conditions that may influence boreal communities' abilities to shift to favorable new climate spaces. The use of projected daily climate data and/or data based on the statistical characteristics of daily variability is highly recommended for future studies. Using daily climate data has improved the model's "generality" and by extension confidence in the utility of FORSKA-2V+ to assess effects of future changes in climate and climate variability at sites in boreal Canada, including where environmental conditions may be much changed from the present.

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Appendix 1. Acronyms

General

AET	actual evapotranspiration
BOREAS	BOReal Ecosystem-Atmosphere Study
DBH	stem diameter at breast height (1.3m above ground)
DD	decimal degrees
GDD	growing degree days, a growing season heat index correlated with plant growth
FORSKA2	patch model developed to study boreal ecosystems in Europe
FORSKA-2V	patch model derived from FORSKA2 for the central Canadian boreal forest and to include inter-annual monthly variability
FORSKA-2V+	patch model derived from FORSKA-2V model code, and modified to include daily climate variability
PET	potential evapotranspiration
SLC	Agriculture Canada Soil Landscapes of Canada (SLC) database

Species Parameters and Model Variables

ADDCCP	the difference in CO2 from present levels (ppm)
AMDEST	species' modified establishment rate
AMDGSC	species' amended growth rate
DGE	dead tree growth efficiency
DRMX	multiplier representing the sensitivity of species to available soil water conditions
GDD	growing degree days
GDDMX	multiplier indicating if species GDD requirements for growth and establishment are met
GSDRI	deciduous growing season drought index
GSINS	deciduous growing season average light intensity
M4DRI	conifer growing season drought index
M4INS	conifer growing season average light intensity
MUTMX	sapwood respiration
PMX	the ratio of assimilation at the forest floor to assimilation in full light
SAPRES	effect of temperature on sapwood respiration
SPT	number of sprouts per tree
SMN	minimum diameter for sprouting (cm)
TCMX	multiplier indicating if mean temperature of the coldest month is within a species tolerance
TCOLD	mean temperature of the coldest month
TFTMX	multiplier representing the annual effect of daily temperature on species net assimilation
TWARM	mean temperature of the warmest month
TWARMX	multiplier indicating if species growing season temperature requirements for regeneration have been met
TWMX	multiplier indicating if species winter chilling requirements have been met
WATC	plant-available soil water holding capacity (mm)

Appendix 2. Species Parameters

	ABBA	**BEPA**	**LALA**	**PIGL**	**PIMA**	**PIBA**	**PIST**	**POBA**	**POTR**	**THOC**
	Abies balsamea	*Betula papyrifera*	*Larix laricina*	*Picea glauca*	*Picea mariana*	*Pinus banksiana*	*Pinus contorta*	*Populus balsamifera*	*Populus tremuloides*	*Thuja occidentalis*
	balsam fir	white birch	tamarack	white spruce	black spruce	jack pine	eastern white pine	balsam poplar	trembling aspen	eastern white cedar
maximum height (m)	27	30	35	55	27	30	48	30	36.5	30
initial slope of diameter vs height (m/cm)	0.76	1.33	0.65	1	0.82	1	1.05	1.26	1.25	1
half-saturation point (umol/m^2/s)	100	330	330	100	100	330	330	330	330	100
compensation point (umol/ m^2/s)	27	40	60	27	20	60	60	40.5	40	27
growth constant (cm^2/m/yr)	14.3	128.4	65.7	16.3	12.4	69.5	77.5	145.4	150	18.9
sapling establishment rate (/ha/yr)	8	10	10	10	10	20	5	3	10	10
threshold relative growth efficiency for increased mortality	0.025	0.04	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025
intrinsic mortality rate (/yr)	0.005	0.01	0.003	0.001	0.004	0.007	0.002	0.01	0.01	0.003
suppressed mortality rate (/yr)	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
number of sprouts per tree (0.0 or greater)	0	1	0	0	1	0	0	3	3	3
minimum diameter for sprouting (cm)	0	10	0	0	10	0	0	20	15	5
initial leaf area/D2 ratio (m^2/cm^2)	0.25	0.07	0.1	0.32	0.32	0.13	0.13	0.08	0.09	0.25
sapwood turnover rate (/yr)	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
stemwood biomass conversion factor (kg/cm^2/m)	0.02	0.03	0.03	0.02	0.02	0.02	0.02	0.03	0.03	0.02

volumetric sapwood maintenance cost (/yr)	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015
rate of increase of respiration	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
minimum temperature for assimilation	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4
maximum temperature for assimilation	36	42	36	36	36	36	36	42	42	36
CO_2 compensation point	80	80	80	80	80	80	80	80	80	80
maximum tolerated drought-index	0.245	0.378	0.05	0.245	0.13	0.53	0.45	0.378	0.45	0.05
minimum growing degree-days (base 5°C)	400	400	400	300	300	600	1100	400	400	1000
minimum temperature of coldest month (°C)	-25	-55	-99.9	-50	-55	-40	-19	-99.9	-99.9	-20
maximum temperature of coldest month (°C)	-5	-2.5	-5	-5	-5	-2.5	2	-4	0	-4
minimum temperature of warmest month (°C)	7.5	7.5	4	5	5	5	10	7.5	5	10
Deciduous (0) or evergreen (1)	1	0	0	1	1	1	1	0	0	1

Appendix 3. Summary table of simulation results (proportion of hardwood versus softwood biomass and stem densities, total stand biomass and stem densities) for each site with a) FORSKA-2V, b) FORSKA-2V+ with new post-fire regeneration modifications (section 5) and c) FORSKA-2V+ with changes to species' establishment rates (section 6.4.3) compared to observed values. Simulations are with daily (D), monthly mean (M) and constant (C) climate inputs and with WATC set to 120, 150 and 200mm and with additional simulations at Thompson at 250 mm and at Rosthern at 100mm. Shaded areas denotes the sites' reference WATC.

	WASKESIU LAKE	Biomass Density (%)		Stem Density (%)		Total Biomass (Mg/ha)	Total Density (stems/ha)
		Hardwood	Softwood	Hardwood	Softwood		
	Expected Values	60	40	60	40	85	
a)	**Pre-Modification**						
	WATC120 (D)	43	57	29	71	60	1048
	WATC120 (M)	22	78	30	70	68	1048
	WATC120 (C)	9	91	23	77	78	1467
	WATC150 (D)	17	83	29	71	73	1061
	WATC150 (M)	17	83	29	71	75	1076
	WATC150 (C)	9	91	23	77	80	1424
	WATC200 (D)	13	87	27	73	74	1135
	WATC200 (M)	14	86	28	72	73	1161
	WATC200 (C)	9	91	23	77	78	1460
b)	**Post-Modification**						
	WATC120 (D)	48	52	28	72	73	895
	WATC120 (M)	49	51	28	72	73	943
	WATC120 (C)	25	75	21	79	73	1046
	WATC150 (D)	44	56	28	72	75	937
	WATC150 (M)	41	59	26	74	75	916
	WATC150 (C)	24	76	21	79	72	1042
	WATC200 (D)	30	70	22	78	70	942
	WATC200 (M)	31	69	22	78	74	927
	WATC200 (C)	24	76	20	80	73	1033
c)	**Establishment Rate Changes**						
	WATC120 (D)	63	37	36	64	80	1266
	WATC150 (D)	48	52	33	67	87	1245
	WATC200 (D)	35	65	27	73	83	1314

	FLIN FLON	Biomass Density (%)		Stem Density (%)		Total Biomass (Mg/ha)	Total Density (stems/ha)
		Hardwood	Softwood	Hardwood	Softwood		
	Expected Values	25	75	25	75	75	
a)	**Pre-Modification**						
	WATC120 (D)	23	77	28	72	29	859
	WATC120 (M)	25	75	30	70	46	951
	WATC120 (C)	13	87	28	72	68	1275
	WATC150 (D)	23	77	28	72	44	984
	WATC150 (M)	24	76	30	70	50	1021
	WATC150 (C)	13	87	28	72	65	1297

	WATC200 (D)	20	80	31	69	61	1053
	WATC200 (M)	17	83	31	69	64	1050
	WATC200 (C)	12	88	28	72	69	1254
b)	**Post-Modification**						
	WATC120 (D)	29	71	25	75	27	747
	WATC120 (M)	37	63	26	74	43	820
	WATC120 (C)	26	74	23	77	67	947
	WATC150 (D)	30	70	23	77	43	878
	WATC150 (M)	37	63	24	76	48	897
	WATC150 (C)	26	74	23	77	62	980
	WATC200 (D)	44	56	27	73	62	909
	WATC200 (M)	42	58	27	73	61	919
	WATC200 (C)	26	74	23	77	65	968
c)	**Establishment Rate Changes**						
	WATC120 (D)	34	66	30	70	32	1047
	WATC150 (D)	38	62	28	72	49	1155
	WATC200 (D)	48	52	32	68	72	1249

	THOMPSON	Biomass Density (%)		Stem Density (%)		Total Biomass (Mg/ha)	Total Density (stems/ha)
		Hardwood	Softwood	Hardwood	Softwood		
	Expected Values	25	75	25	75	60	
a)	**Pre-Modification**						
	WATC120 (D)	13	87	27	73	61	1056
	WATC120 (M)	11	89	29	71	64	1057
	WATC120 (C)	10	90	31	69	61	1093
	WATC150 (D)	12	88	27	73	63	1043
	WATC150 (M)	12	88	31	69	59	1113
	WATC150 (C)	11	89	32	68	60	1097
	WATC200 (D)	11	89	30	70	62	1087
	WATC200 (M)	12	88	31	69	59	1113
	WATC200 (C)	11	89	32	68	62	1081
b)	**Post-Modification**						
	WATC120 (D)	25	75	22	78	58	894
	WATC120 (M)	21	79	22	78	59	863
	WATC120 (C)	20	80	24	76	56	879
	WATC150 (D)	22	78	22	78	58	878
	WATC150 (M)	21	79	23	77	54	894
	WATC150 (C)	19	81	23	77	53	888
	WATC200 (D)	21	79	23	77	55	905
	WATC200 (M)	21	79	23	77	54	894
	WATC200 (C)	20	80	23	77	55	892
c)	**Establishment Rate Changes**						
	WATC120 (D)	28	72	26	74	68	1245
	WATC150 (D)	25	75	26	74	66	1259
	WATC200 (D)	24	76	26	74	68	1249

	FORT SMITH	Biomass Density (%)		Stem Density (%)		Total Biomass (Mg/ha)	Total Density (stems/ha)
		Hardwood	Softwood	Hardwood	Softwood		
	Expected Values	40	60	40	60	75	
a)	**Pre-Modification**						
	WATC120 (D)	23	77	31	69	30	727
	WATC120 (M)	45	55	34	66	42	833
	WATC120 (C)	15	85	28	72	63	1071
	WATC150 (D)	36	64	30	70	46	892
	WATC150 (M)	27	73	29	71	47	929
	WATC150 (C)	14	86	29	71	62	1092
	WATC200 (D)	33	67	32	68	56	1026
	WATC200 (M)	27	73	30	70	55	1014
	WATC200 (C)	12	88	30	70	65	1084
b)	**Post-Modification**						
	WATC120 (D)	21	79	26	74	32	636
	WATC120 (M)	53	47	32	68	44	724
	WATC120 (C)	29	71	22	78	59	910
	WATC150 (D)	43	57	27	73	49	804
	WATC150 (M)	37	63	25	75	47	840
	WATC150 (C)	26	74	23	77	59	897
	WATC200 (D)	51	49	27	73	59	925
	WATC200 (M)	45	55	26	74	57	899
	WATC200 (C)	26	74	24	76	56	913
c)	**Establishment Rate Changes**						
	WATC120 (D)	33	67	37	63	34	864
	WATC150 (D)	55	45	36	64	57	1089
	WATC200 (D)	57	43	33	67	73	1238

	ENNADAI LAKE	Biomass Density (%)		Stem Density (%)		Total Biomass (Mg/ha)	Total Density (stems/ha)
		Hardwood	Softwood	Hardwood	Softwood		
	Expected Values	0	100	0	100	10	
a)	**Pre-Modification**						
	WATC120 (D)	23	77	35	65	2	91
	WATC120 (M)	6	94	25	75	0	33
	WATC120 (C)	11	89	37	63	37	263
	WATC150 (D)	2	98	23	77	27	97
	WATC150 (M)	3	97	23	77	1	36
	WATC150 (C)	11	89	38	62	35	273

	WATC200 (D)	1	99	17	83	33	90
	WATC200 (M)	3	97	23	77	1	41
	WATC200 (C)	11	89	39	61	35	282
b)	**Post-Modification**						
	WATC120 (D)	36	64	36	64	1	204
	WATC120 (M)	10	90	25	75	0	105
	WATC120 (C)	20	80	34	66	29	529
	WATC150 (D)	4	96	26	74	15	307
	WATC150 (M)	5	95	23	77	0	123
	WATC150 (C)	19	81	35	65	28	540
	WATC200 (D)	2	98	16	84	24	423
	WATC200 (M)	3	97	21	79	1	137
	WATC200 (C)	16	84	35	65	29	539
c)	**Establishment Rate Changes**						
	WATC120 (D)	35	65	37	63	3	396
	WATC150 (D)	5	95	26	74	22	547
	WATC200 (D)	2	98	16	84	31	726

	ROSTHERN	Biomass Density (%)		Stem Density (%)		Total Biomass	Total Density
		Hardwood	Softwood	Hardwood	Softwood	(Mg/ha)	(stems/ha)
	Expected Values	100	0	100	0	30	
a)	**Pre-Modification**						
	WATC100 (D)	10	90	25	75	10	413
	WATC100 (M)	27	73	28	72	52	833
	WATC100 (C)	18	82	24	76	80	1456
	WATC120 (D)	60	40	39	61	47	756
	WATC120 (M)	66	34	36	64	84	993
	WATC120 (C)	16	84	23	77	85	1417
	WATC150 (D)	62	38	36	64	80	1046
	WATC150 (M)	67	33	40	60	94	1065
	WATC150 (C)	17	83	24	76	82	1464
b)	**Post-Modification**						
	WATC100 (D)	11	89	23	77	10	375
	WATC100 (M)	27	73	24	76	50	747
	WATC100 (C)	38	62	21	79	86	1037
	WATC120 (D)	60	40	35	65	50	656
	WATC120 (M)	72	28	34	66	107	881
	WATC120 (C)	38	62	21	79	85	1051
	WATC150 (D)	63	37	34	66	94	896
	WATC150 (M)	76	24	36	64	110	952
	WATC150 (C)	36	64	21	79	86	1052
	WATC200 (D)	57	43	29	71	92	940
	WATC200 (M)	57	43	28	72	90	937

WATC200 (C)	35	65	22	78	87	1033

c) Establishment Rate Changes

WATC120 (D)	75	25	48	52	67	912
WATC150 (D)	76	24	44	56	113	1209
WATC200 (D)	60	40	35	65	105	1257

Appendix 4. Results of sensitivity tests on aspen's prescribed sprouting paramters at Rosthern (WATC 120mm) and Waskesiu Lake (WATC 150 mm). Note: "no DGE criteria" refers to tests with aspen's maximum number of sprouts permitted.

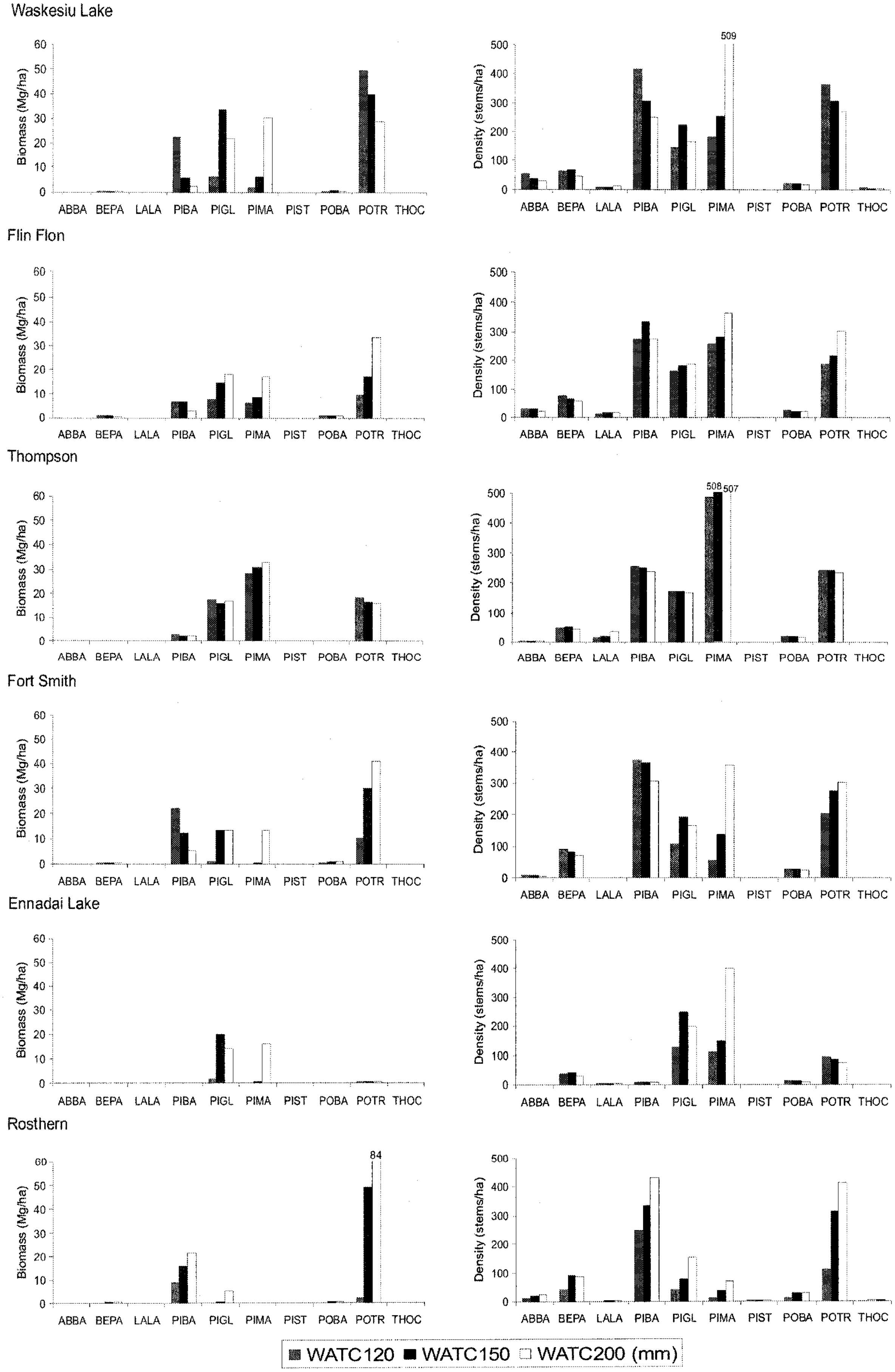
ROSTHERN

		current sprouting rates and parameters	sprouting off	diameter requirement reduced to 10cm	sprouting rate increased to 6	diameter requirement 10cm & sprouting rate 6	no DGE criteria (maximum number of sprouts permitted, 3)	no DGE criteria & diameter 10cm	no DGE criteria & sprouting rate 6	no DGE criteria, diameter 10cm & sprouting rate 6	seeding rate 15 (+50%)	seeding rate 20 (+100%)	seeding rate 1.5 & sprouting rate 30	seeding rate 10 & sprouting rate 30
Increase in Sprouting		reference	N/A	5x	3x	9.5x	11x	28x	40x		2.7x	5x	48x	70x
Biomass														
Aspen	(Mg/ha)	29	26	29	31	35	41	57	71	115	37	49	33	78
	% change		-12%	0%	8%	20%	41%	98%	144%	295%	27%	69%	14%	168%
Jack pine														
	(Mg/ha)	19	21	20	19	18	17	16	15	8	17	16	21	13
	% change		10%	1%	-3%	-6%	-11%	-18%	-23%	-58%	-13%	-18%	8%	-33%
Total Site Biomass	(Mg/ha)	29	26	29	31	35	41	57	86	115	57	65	54	91
Density														
Aspen														
	(stems/ha)	164	140	175	190	226	259	395	548	1450	239	312	250	704
	% change		-14%	7%	16%	38%	58%	141%	235%	785%	46%	91%	53%	330%
Jack pine														
	(stems/ha)	350	352	354	350	350	344	336	321	275	351	341	349	313
	% change		1%	1%	0%	0%	-2%	-4%	-8%	-21%	0%	-3%	0%	-11%

WASKESIU

		current sprouting rates and parameters	sprouting off	diameter requirement reduced to 10cm	sprouting rate increased to 6	diameter requirement 10cm & sprouting rate 6	no DGE criteria (maximum number of sprouts permitted, 3)	no DGE criteria & diameter 10cm	no DGE criteria & sprouting rate 6	no DGE criteria, diameter 10cm & sprouting rate 6	seeding rate 15 (+50%)	seeding rate 20 (+100%)	seeding rate 1.5 & sprouting rate 30	seeding rate 10 & sprouting rate 30
Increase in Sprouting		reference	N/A	7x	5x	14x	17x	33x	42x		3.6x	3x	1.8x	23x
Biomass														
Aspen	(Mg/ha)	32	29	34	36	40	44	48	46	57	45	54	15	52
	% change		-10%	5%	12%	24%	37%	50%	44%	80%	41%	69%	-53%	63%
Jack pine	(Mg/ha)	11	11	11	10	11	10	10	10	9	10	9	13	10
	% change		3%	-1%	-6%	-3%	-10%	-9%	-10%	-16%	-10%	-19%	17%	-10%
W. spruce		26	26	26	29	23	26	25	23	21	24	33	29	25
B. spruce		4	4	4	4	4	4	4	4	4	4	4	4	4
Total Site Biomass	(Mg/ha)	73	70	75	79	78	84	88	85	92	84	91	63	92
Density														
Aspen	(stems/ha)	187	166	203	207	252	274	361	387	637	273	367	97	383
	% change		-11%	8%	11%	35%	46%	93%	107%	241%	46%	96%	-48%	105%
Jack pine	(stems/ha)	366	371	364	354	372	357	350	364	350	365	361	368	348
	% change		1%	-1%	-3%	2%	-3%	-4%	0%	-4%	0%	-1%	1%	-6%
W. spruce	(stems/ha)	146	146	146	145	142	142	141	138	137	138	139	148	139
B. spruce	(stems/ha)	137	134	137	132	136	149	145	151	146	151	138	133	133

Appendix 5. Simulated species biomass and stem densities at each site with FORSKA-2V+ and changes to species' establishment rates (section 6.4.3) Simulations are with daily climate input data and with WATC set to 120 (gray), 150 (black) and 200 (white) mm, except Rosthern at 100 (gray), 120 (black) and 150 (white) mm. Species abbreviations: *Abies balsamea* (ABBA), *Betula papyrifera* (BEPA), *Larix laricina* (LALA), *Picea glauca* (PIGL), *Picea mariana* (PIMA), *Pinus banksiana* (PIBA), *Pinus strobus* (PIST), *Populus balsamifera* (POBA), *Populus tremuloides* (POTR), and *Thuja occidentalis* (THOC).



Waskesiu Lake
Flin Flon
Thompson
Fort Smith
Ennadai Lake
Rosthern
Biomass (Mg/ha)
Density (stems/ha)
0
10
20
30
40
50
60
100
200
300
400
500
ABBA
BEPA
LALA
PIBA
PIGL
PIMA
PIST
POBA
POTR
THOC
509
508
507
84
▨ WATC120 ■ WATC150 □ WATC200 (mm)

Appendix 6. FORSKA-2V+ Environmental and Population DynamicsSub-Model Code

```
          PROGRAM ENVIROD
          IMPLICIT NONE

* FORSKAC - 2L - LANDSCAPE version 1990

*TLS Special Edition to read Daily Data 2006

* DTP This program is the climate portion of FORSKA2, which reads
* in the climate data file, "dlyclim.txt", converts it into a file
* of climate multipliers which is then saved in "envirod.inp". This
* file is then available to be read in by FORSKA2.  A switch can
* be set at the bottom of the PARAM.DAT file to indicate whether
* climate data are to be read in from "dlyclim.txt", or whether
* environmental data are to be read in from envirod.inp, and the
* getenv portion of FORSKA should be bypassed.
* TLS The getenv routine in FORSKA was removed. All climate data
* processed in ENVIRO.

* Model to simulate the dynamics of forest stand composition and
* structure. Version 1.1 created August 1988 by Colin Prentice and
* Rik Leemans, Institute of Ecological Botany, Uppsala University,
* Box 559, S-751 22 Uppsala, Sweden
*
* Version 2L amended to include climate and disturbance
*  by Colin Prentice and Martin Sykes  Uppsala 1990

* DTP Alterations to original code added by Dave Price are marked with
* my initials (as here). Also, some modifications have been added by Sean
* Sampson, marked 'SS'.

* TLS modifications marked with TLS

c on UNIX, compile with "f77 -u" - to warn of undeclared variables

* dimensions and device names
* MAXSPE = maximum number of species
* MAXPAT = maximum number of patches
* MAXIND = maximum number of trees per patch
* MAXTIM = maximum number of years

* SYSOUT = standard output device (console, screen)
* SYSIN  = standard input device  (console, keyboard)

      INCLUDE 'compar.h'

* TLS global model parameters (MAXSPE, MAXPAT, MAXIND,MAXTIM,MAXDSI,MAXDIS,
* MAXACL) moved to common file compare.h.

      INTEGER SYSOUT,SYSIN
```

```
* input and output devices for VAX/VMS and IBM/PC-AT

      PARAMETER(SYSOUT=6,SYSIN=5)

* input and output devices for Macintosh (Absoft or Microsoft Fortran Compiler)

C     PARAMETER(SYSOUT=9,SYSIN=9)

* run parameters

      INTEGER NPAT,NTIM,NTAX,TIM,TIMRET,GAMMA
      REAL*4    KCO,PAT,VINC,DBH0,RHO,TREF,FCO2
      COMMON /MODEL/KCO,NPAT,NTIM,PAT,TIM,NTAX,VINC,DBH0,RHO,TREF,FCO2,
     %              TIMRET,GAMMA

* site parameters

      REAL*4    WMX,WATC           ! WATC is the soil's "maximum water capacity"
      COMMON /SITE/ WMX,WATC      ! Formerly named FCAP, but considered
misleading

* species parameters (includes species climate response parameters)

      REAL*4    HMX(MAXSPE),HDS(MAXSPE),ALP(MAXSPE),LCP(MAXSPE),
     +        GSC(MAXSPE),EST(MAXSPE),TDI(MAXSPE),UMN(MAXSPE),
     +        UMX(MAXSPE),SPR(MAXSPE),SMN(MAXSPE),
     +        LAC(MAXSPE),LAF(MAXSPE),GOP(MAXSPE),
     +        BCF(MAXSPE),R(MAXSPE),Q10(MAXSPE),TMIN(MAXSPE),
     %        TMAX(MAXSPE),CCP(MAXSPE),
     +        DRI(MAXSPE),PRO(MAXPAT,MAXSPE),MINGDD(MAXSPE),
     +        MINTC(MAXSPE),MAXTC(MAXSPE),MINTW(MAXSPE)
      INTEGER DORE(MAXSPE)
      COMMON /TAXA/HMX,HDS,ALP,LCP,GSC,EST,TDI,UMN,UMX,SPR,SMN,
     +             LAC,LAF,GOP,BCF,R,Q10,TMIN,TMAX,CCP,PRO,DRI,
     %             MINGDD,MINTC,MAXTC,MINTW,DORE

      CHARACTER*8 NAM(MAXSPE)
      COMMON /NAMES/ NAM

      REAL*4    INC(MAXPAT,MAXSPE)
      COMMON /DBHST/INC


* common for environmental variables and multipliers.

      REAL*4    GDD(MAXTIM),GSDRI(MAXTIM),M4DRI(MAXTIM),GSINS(MAXTIM),
     %        M4INS(MAXTIM),TCOLD(MAXTIM),TWARM(MAXTIM),ADDCCP(MAXTIM),
     %        MUTMX(MAXSPE,MAXTIM),SAPRES(MAXSPE,MAXTIM),
     %        TFTMX(MAXSPE,MAXTIM)
      INTEGER YR(MAXTIM)
      COMMON /CLIMO/GDD,GSDRI,M4DRI,GSINS,M4INS,TCOLD,TWARM,ADDCCP,YR,
```

```
     %                 MUTMX,SAPRES,TFTMX


*DTP -- I added these to check on annual water balance calculations...
      REAL*4 totsol,totnet,totppt,totpet,totaet,totrno
      COMMON /YRTOTS/totsol,totnet,totppt,totpet,totaet,totrno


* reading or initializing parameters

      CALL LGTMOD(SYSOUT,SYSIN)
      CALL CGTSPE(SYSOUT,NTAX)
      CLOSE(UNIT=1)

* reads in basic CLIMATE data to be worked on to produce gdd etc.
* call to bucket and environmental routines

      CALL GTCLIM(SYSOUT)   !TLS changed from GETENV as PCLahey
                            !compiler did not accept

* initialize VAX/VMS screen display

C       call init_disp(ib,is,it,ist,ih_a,ih_b,i_a,i_b,iyr,i1,i2)

*DTP  PAUSE 'Forska ENVIROD normal termination. Press RETURN to quit.'
      WRITE(SYSOUT,2)
      STOP ' '

* format statements:

2     FORMAT(/' ** ENVIROD - Normal Termination **')
      END


*****************************************************************************

      SUBROUTINE LGTMOD(SYSOUT,SYSIN)
      IMPLICIT NONE

* landscape version 1990
* reads model parameters from file PARAMBF.DAT

      INTEGER MAXSPE,MAXPAT,MAXIND

      INTEGER SYSOUT,SYSIN

      REAL*4    WMX,WATC
      COMMON /SITE/ WMX,WATC

      INTEGER NPAT,NTIM,NTAX,TIM,TIMRET,GAMMA
      REAL*4    KCO,PAT,VINC,DBH0,RHO,TREF,FCO2
      COMMON /MODEL/KCO,NPAT,NTIM,PAT,TIM,NTAX,VINC,DBH0,RHO,TREF,FCO2,
```

```
     %                TIMRET,GAMMA

      CHARACTER*80 TITLE
      CHARACTER*40 FILENM

* opens input and output files

      OPEN(UNIT=1,FILE='PARAMBF.DAT',STATUS='OLD',ERR=100)
      GOTO 200

100   WRITE(SYSOUT,1)
101   WRITE(SYSOUT,2)
      READ(SYSIN,'(A40)')FILENM
      IF(FILENM(1:5).EQ.'     ')
     +                  STOP ' STOPPED: FILE SPECIFIED NOT VALID'
      OPEN(UNIT=1,FILE=FILENM,STATUS='OLD',ERR=102)
      GOTO 200
102   WRITE(SYSOUT,3)
      GOTO 101

200   OPEN(UNIT=12, FILE='mltpd.inp', STATUS='UNKNOWN')
      OPEN(UNIT=3,FILE='envirod.inp',STATUS='UNKNOWN')
      OPEN(UNIT=5,FILE='test.dat',STATUS='UNKNOWN')
      OPEN(UNIT=13,FILE='indexd.dat',STATUS='UNKNOWN')

* TLS 'mltpd.inp' and 'indexd.dat' added to separate out species multipliers
* from environmental multipliers.

* reads and writes title and subtitle of the run

      READ(1,4,ERR=999,END=999)TITLE
      WRITE(SYSOUT,'(1X,A79)')TITLE(1:79)
*      WRITE(3,'(1X,A80)')TITLE

      READ(1,4,ERR=999,END=999)TITLE
      WRITE(SYSOUT,6)TITLE(1:79)
*      WRITE(3,5)TITLE


*********************************************************
** N.B. Colin Prentice pointed out that FCP is not really
** the "field capacity" but (FCP - WP) = max available soil
**              water storage

** DTP 93/05/07  Experiment with modified values for
**     Timret and Gamma - The disturbance return interval and
**     conditional probability factor
*********************************************************

* reads and writes site parameters:

* WMX:   max biomass (Mg/ha),
```

```
* WATC:  size of bucket (field capacity)

      READ(1,*,ERR=999,END=999)WMX,WATC
      WRITE(SYSOUT,7)WMX,WATC
*     WRITE(3,7)WMX,WATC

* reads and writes MODEL run parameters:

* KCO:  light extinction coefficient,
* PAT:  patch size (ha),
* NPAT: number of patches,
* TIM:  timestep (yr),
* NTIM: number of timesteps,
* VINC: vertical integration step (m),
* DBH0: minimum diameter (cm),
* RHO:  steepness parameter for the mortality function
* TREF: reference temperature
* FCO2: internal/external CO2
* TIMRET: mean recurrence interval for disturbance
* GAMMA:  disturbance rate


      READ(1,*,ERR=999,END=999)KCO,PAT,NPAT,TIM,NTIM,VINC,DBH0,RHO,TREF,
     %                         FCO2,TIMRET,GAMMA
      WRITE(SYSOUT,9)KCO,PAT,NPAT
*      WRITE(3,9)KCO,PAT,NPAT

      WRITE(SYSOUT,10)TIM,NTIM,TREF
*      WRITE(3,10)TIM,NTIM,TREF

      IF(RHO.LE.20)THEN
         WRITE(SYSOUT,11)VINC,RHO
*         WRITE(3,11)VINC,RHO
      ELSE
         WRITE(SYSOUT,12)VINC,RHO
*         WRITE(3,12)VINC,RHO

      ENDIF
      WRITE(SYSOUT,13)DBH0
*      WRITE(3,13)DBH0

      WRITE(SYSOUT,14)FCO2
*      WRITE(3,14)FCO2

      WRITE(SYSOUT,15)TIMRET,GAMMA
*      WRITE(3,15)TIMRET,GAMMA

      GOTO 1000 ! Skip to end to keep the 999 label in the block.....(OH
FORTRAN!!!)

999   WRITE(SYSOUT,20)
      WRITE(3,20)
```

```
*DTP  PAUSE 'Press RETURN to quit.'
      STOP 'Forska ENVIROD terminated because of read error(s).'


1000  CONTINUE
*DTP  PAUSE 'Press RETURN to continue.'
      RETURN


* format statements

1     FORMAT(/' ERROR...... File PARAMBF.DAT not found!')
2     FORMAT(/' Type new FILENAME: '$)
3     FORMAT(/' FILE NOT FOUND. RE-ENTER......')
4     FORMAT(A80)
5     FORMAT(1X,A80//1X,130('-'))
6     FORMAT(/1X,A79//1X,A79/1X,79('-'))
7     FORMAT(/' SITE PARAMETERS'//2X,'max stemwood biomass',24X,F6.1,
     %       7X,'Mg/ha'/2X,'bucket size (field capacity)',16X,F6.1,
     %       7X,'mm')
9     FORMAT(/' MODEL PARAMETERS'//2X,'light extinction coefficient',
     %       15X,F8.2/2X,'patch size',36X,F6.3,
     +'     ha'/2X,'number of patches',27X,I4)
10    FORMAT(2X,'timestep',36X,I4,9X,'yr'/
     +       2X,'number of timesteps',25X,I4,/
     %       2X,'reference temperature',23X,F6.1,'   oC')
11    FORMAT(2X,'vertical integration step',21X,F5.2,6X,'m'/2X
     +,'steepness parameter',25X,F6.1,7X,'(Continuous function)')
12    FORMAT(2X,'vertical integration step',21X,F5.2,6X,'m'/
     +2X,'steepness parameter',25X,F6.1,7X,'(step function)')
13    FORMAT(2X,'minimum starting diameter',20X,F7.2,5X,'cm')
14    FORMAT(2X,'internal/external CO2',24X,F7.2)
15    FORMAT(2X,'disturbance mean recurrence interval',9X,I4,/
     %       2X,'disturbance rate',29X,I4/)
20    FORMAT(/' ERROR IN READING MODEL PARAMETERS')

      END   !LGTMOD

*****************************************************************************

      SUBROUTINE CGTSPE(SYSOUT,NTAX)
      IMPLICIT NONE

* CLIMATE and LANDSCAPE version 89.10.23

* reads species parameters

      INCLUDE 'compar.h'    ! TLS moved global model parameters

      CHARACTER*8 NAM(MAXSPE)
      COMMON /NAMES/ NAM
```

```
      REAL*4    HMX(MAXSPE),HDS(MAXSPE),ALP(MAXSPE),LCP(MAXSPE),
     +        GSC(MAXSPE),EST(MAXSPE),TDI(MAXSPE),UMN(MAXSPE),
     +        UMX(MAXSPE),SPR(MAXSPE),SMN(MAXSPE),
     +        LAC(MAXSPE),LAF(MAXSPE),GOP(MAXSPE),
     %        BCF(MAXSPE),R(MAXSPE),Q10(MAXSPE),TMIN(MAXSPE),
     %        TMAX(MAXSPE),CCP(MAXSPE),
     +        DRI(MAXSPE),PRO(MAXPAT,MAXSPE),MINGDD(MAXSPE),
     +        MINTC(MAXSPE),MAXTC(MAXSPE),MINTW(MAXSPE)
      INTEGER DORE(MAXSPE)
      COMMON /TAXA/HMX,HDS,ALP,LCP,GSC,EST,TDI,UMN,UMX,SPR,SMN,
     +             LAC,LAF,GOP,BCF,R,Q10,TMIN,TMAX,CCP,PRO,DRI,
     %             MINGDD,MINTC,MAXTC,MINTW,DORE

* local variables

C     REAL*4    CHECK
      INTEGER SYSOUT,NTAX,I

* reads number of taxa (NTAX)

      READ(1,*,ERR=999,END=999)NTAX

* reads for each taxon:

*   NAM(I): name (8 characters)
*   HMX(I): max height (m)
*   HDS(I): initial slope of diameter vs height (m/cm)
*   ALP(I): half-saturation point (umol/m**2/s)
*   LCP(I): compensation point (umol/m**2/s)
*   GSC(I): growth constant (cm**2/m/yr)
*   EST(I): sapling establishment rate (/ha/yr)
*   TDI(I): threshold relative growth efficiency for increased mortality
*   UMN(I): intrinsic mortality rate (/yr)
*   UMX(I): suppressed mortality rate (/yr)
*   SPR(I): number of sprouts per tree (0.0 or greater)
*   SMN(I): minimum diameter for sprouting (cm)
*   LAC(I): initial leaf area/D2 ratio (m**2/cm**2)
*   LAF(I): sapwood turnover rate (/yr)
*   BCF(I): stemwood biomass conversion factor (kg/cm**2/m)
*     R(I): volumetric sapwood maintenance cost (/yr)
*   Q10(I): rate of increase of respiration
*  TMIN(I): minimum temperature for assimilation
*  TMAX(I): maximum temperature for assimilation
*   CCP(I): species compensation point
*   DRI(I): maximum tolerated drought-index
*MINGDD(I): minimum growing degree-days
* MINTC(I): minimum temperature of coldest month (degrees C)
* MAXTC(I): maximum temperature of coldest month (degrees C)
* MINTW(I): minimum temperature of warmest month (degrees C)
*  DORE(I): deciduous or evergreen 0=deciduous,1=evergreen
```

```
      DO 100 I=1,NTAX
*        READ(1,1,ERR=999,END=999) NAM(I)
         READ(1,*,ERR=999,END=999) NAM(I),HMX(I),HDS(I),ALP(I),LCP(I),
     +                             GSC(I),EST(I),TDI(I),UMN(I),UMX(I),
     +                             SPR(I),SMN(I),LAC(I),LAF(I),BCF(I),
     %                             R(I),Q10(I),TMIN(I),TMAX(I),CCP(I),
     +                             DRI(I),MINGDD(I),MINTC(I),
     +                             MAXTC(I),MINTW(I),DORE(I)

         IF(SPR(I).EQ.0)SMN(I)=0.0

         IF(MINTC(I).GT.MAXTC(I))THEN
            WRITE (SYSOUT,30)I
            WRITE (3,30)I
            STOP 'ENVIROD terminated -- minimum Tc exceeds maximum Tc.'
         ENDIF
100      CONTINUE

      RETURN

* error messages

999   WRITE(SYSOUT,30)I
      WRITE(3,30)I
*DTP  PAUSE 'Press RETURN to quit.'
      STOP 'ENVIROD terminated because of read error(s).'

* format statements

  1   FORMAT(A8)
 30   FORMAT(/' Error reading input data for species ',I2)

      END   !CGTSPE

*******************************************************************************

      SUBROUTINE GTCLIM(SYSOUT)
      IMPLICIT NONE

* gets and prepares environmental data for use in FORSKA,
* uses climate data as input into Wolfgang Cramer's amended routines
* which then work out gdd, thermal multipliers, drought index,
* light intensity, temp coldest month, temp. warmest month
*
* CLIMATE and LANDSCAPE version 89.10.24
* written by Colin Prentice and Martin Sykes
*
* ENVSUB routines amended and corrected
* reads and ignores range (MTR) no longer used anywhere September 1991
* Martin Sykes

      INCLUDE 'compar.h'    ! TLS moved global model parameters
```

```
      integer sysout

* common environmental variables
*
* gdd    - growing degree days - site
* gsdri  - growing season drought index - site
* m4dri  - -4 oC drought index - site
* gsins  - growing season average light intensity - site (dpar)
* m4ins  - -4 oC season average light intensity - site (dpar)
* tcold  - temperature coldest month  - site
* twarm  - temperature warmest month  - site
* addccp - the difference in CO2 from today (ppm) - site
* sapres - sapwood respiration - species specific = old del
* tftmx  - thermal multiplier  - species specific


      REAL*4 gdd(maxtim),gsdri(maxtim),m4dri(maxtim),gsins(maxtim),
     %      m4ins(maxtim),tcold(maxtim),twarm(maxtim),addccp(maxtim),
     %      mutmx(maxspe,maxtim),sapres(maxspe,maxtim),
     %      tftmx(maxspe,maxtim)
      integer yr(maxtim)

      common /climo/gdd,gsdri,m4dri,gsins,m4ins,tcold,twarm,addccp,yr,
     %              mutmx,sapres,tftmx

* common for site parameters

      REAL*4  wmx,watc
      common /site/ wmx,watc

* common for model parameters

      integer npat,ntim,ntax,tim,timret,gamma
      REAL*4    kco,pat,vinc,dbh0,rho,tref,fco2
      common /model/kco,npat,ntim,pat,tim,ntax,vinc,dbh0,rho,tref,fco2,
     %              timret,gamma

* common for species parameters

      REAL*4    hmx(maxspe),hds(maxspe),alp(maxspe),lcp(maxspe),
     +        gsc(maxspe),est(maxspe),tdi(maxspe),umn(maxspe),
     +        umx(maxspe),spr(maxspe),smn(maxspe),
     +        lac(maxspe),laf(maxspe),gop(maxspe),
     +        bcf(maxspe),r(maxspe),q10(maxspe),tmin(maxspe),
     %        tmax(maxspe),ccp(maxspe),
     +        dri(maxspe),pro(maxpat,maxspe),mingdd(maxspe),
     +        mintc(maxspe),maxtc(maxspe),mintw(maxspe)
      integer dore(maxspe)
      common /taxa/hmx,hds,alp,lcp,gsc,est,tdi,umn,umx,spr,smn,
     +                           lac,laf,gop,bcf,r,q10,tmin,tmax,ccp,
     %                           pro,dri,mingdd,mintc,maxtc,mintw,dore
```

```
*DTP common for annual totals of water balance terms
      REAL*4 totsol,totnet,totppt,totpet,totaet,totrno
      COMMON /YRTOTS/totsol,totnet,totppt,totpet,totaet,totrno

* local variables

* TLS new variables for use with daily data “dlyclim.txt”
* clou, dlymin, dlymax, prec, are arrays of 365 days of data
* temp (mean daily temp) and tran (range) calculated from dlymin and dlymax
* mtmin, mtmax, mpr, mcl are average monthly values from “mtlyclim.txt”
* mtly (monthly mean) calculated from mtmin and mtmax

      REAL*4 dly(365),mtly(12), clou(365),prec(365),temp(365),tran(365),
     >       mtmin(12), mtmax(12),mpr(12),mcl(12)   !TLS daily
     REAL*4 lat,ldsm,rjunk,ojunk,pjunk,qjunk,dlymin(365),dlymax(365) !daily
c       REAL*4 lat, mtc(12),mtr(12),mpr(12),mcl(12),lmtc,lmtr,lmpr,lmcl,
c    >   nmtc(12),nmtr(12),nmpr(12),nmcl(12),ldsm, mtmin(12),mtmax(12) !monthly


      integer yrno,i,j,k,l,lnblnk
      character*20 stname,timstr, njunk
       character*5  sjunk
      character*24 fdate,datstr
      character*100 linein

      open(10,file='dlyclim.txt',status='old')


* DTP 92/12/09 - I added the following statements so that output from individual
* runs would be stamped with the file type, date, time and climate station name.

* NOTE: FUNCTIONs lnblnk() and fdate() are specific to Sun F77

       read(10, 95, err=999, end=999) linein
  95   format (A100)
       write (sysout,95)linein
       l=lnblnk(linein)


      datstr=fdate()
      timstr=datstr(12:19)
      datstr=datstr(9:11)//datstr(5:8)//datstr(21:24)

      write(3,99)  linein,timstr,datstr
      WRITE(12,99)  linein,timstr,datstr
      WRITE(13,99)  linein,timstr,datstr
      write(sysout,99) linein,timstr,datstr
   99 FORMAT(A100, '.  ENVIROD run at ',A8,' on ',A11)


* read site parameters
```

```
      read(10,*,err=999,end=999) lat,watc,addccp(l)
c  96 format (f3.1)
      write(13,*) lat,watc,addccp(l)

      ldsm = WATC      ! Initialise soil moisture for start of first year
      yrno = 0.0       ! Initialise last day's runoff to 0

* write environmental headings to forcli.out and screen

      write(sysout,100)
*     write(3,100)
      write(sysout,101)
      write(3,101)
      WRITE(12,105)
      write(13,101)
      write(3,601)


* TLS open mtlyclim.txt and read and ignore headers

      open(UNIT=9,file='mtlyclim.txt',status='old')
      read(9,*,ERR=999,end=999) njunk
       read(9,*,ERR=999,end=999) ojunk, pjunk, qjunk

* set up loop to read climate data for each year to ntim*tim

      do l=1,(ntim*tim)
C     do l=1,110      ! This is useful for debugging runs

* TLS read climate data from “dlyclim.txt” in modified input format
* for daily data

*              Temperature data consist of daily Tmin and Tmax


c        read(10,*,err=999,end=999) lat,watc,addccp(l),
c    >                               (mtmin(i),i=1,12),rjunk,sjunk,
c    >                               (mtmax(i),i=1,12),rjunk,sjunk,
c    >                               (mpr(i),i=1,12),rjunk,sjunk,
c    >                               (mcl(i),i=1,12),rjunk,sjunk
c     endif

         read(10,*,err=999,end=999)  (dlymin(i),i=1,365),    ! Tmin
     >                               (dlymax(i),i=1,365),    ! Tmax
     >                               (prec(i),i=1,365),      ! Precip
     >                               (clou(i),i=1,365)       ! Sun%

      do i = 1,365
         tran(i) = dlymax(i) - dlymin(i)              !daily Trange
         temp(i) = (dlymax(i) + dlymin(i))/2          !daily Tmean
        prec(i) = prec(i)*1.1     !tls increase prec by 10% to account
                             ! for under catching
```

```
      enddo

C    IF(1.EQ.30)THEN               !tls option to write yearly arrays
C     OPEN(UNIT=5,FILE='TEST.DAT',STATUS='UNKNOWN')
* to compare with interpolations from monthly data
C     WRITE(5,*)1, prec
C    endif

C      close (10)      ! Close the file


* call environmental subroutines
* First, check to see whether output files should be opened for diagnosing
* environmental submodel data for years 591-600 (1XCO2) and 1191-1200 (2XCO2)
*        IF(1.EQ.591)THEN
           OPEN(UNIT=4,FILE='EVAP1.OUT',STATUS='UNKNOWN')
*          write(4,600)
          write(4,500)
         ENDIF
        IF(1.EQ.1191)THEN
          OPEN(UNIT=4,FILE='EVAP2.OUT',STATUS='UNKNOWN')
*          write(4,600)
          write(4,500)
        ENDIF

        CALL envsub (sysout,Lat,tran,temp,prec,clou,L,lDSM,yrno)

***********************************************************************
* DTP 99/06/24: Changed these for Pingree Park Experiment
*        IF(((1.GE.591).AND.(1.LE.600)).OR.
*     >    ((1.GE.1191).AND.(1.LE.1200))) THEN ! write annual water balance data
*          write(4,602) totsol,totnet,totaet,totpet,totppt,totrno
*        ENDIF
        IF((1.EQ.600).OR.(1.EQ.1200)) CLOSE(UNIT=4)

***********************************************************************
* DTP 99/06/24: Changed these for Pingree Park Experiment
  500     format('Time\tPPT\tAET\tPET\tSM\tDrI')

  600     format('DOY,  DPAR  ,  TEMP  , SUPPLY , SOILW  , GLOBAL ,'
    >            ' NETRAD ,  DAET  ,  DPET  , PRECIP , RUNOFF ')
  601     format('--------------------------------------------------------'
    >            '------------------------')
  602     format(28x,',,,TOTALS:', 6(',',F8.2))

* work out temperatures of coldest and warmest months of year

* DTP Initialise to some ridiculously high and low temperatures.
*     But, -50 C ain't so cold for northern Canada!  However,
*     these are monthly means.

        tcold(1)=50.0
```

```
          twarm(l)=-50.0

*TLS modified to read monthly data only for species tolerance calculations

          read(9,*,ERR=999,end=999) (mtmin(j),j=1,12),rjunk, sjunk,
     >               (mtmax(j),j=1,12),rjunk, sjunk,
     >               (mpr(j),j=1,12),rjunk, sjunk,
     >               (mcl(j),j=1,12),rjunk, sjunk

          do j=1,12
            mtly(j)=(mtmax(j)+mtmin(j))/2
          enddo

          do j=1,12
            if(mtly(j).lt.tcold(l))tcold(l)=mtly(j)
            if(mtly(j).gt.twarm(l))twarm(l)=mtly(j)
          enddo ! j=1,12

          write(sysout,102)l,gdd(l),gsdri(l),m4dri(l),gsins(l),
     %                    m4ins(l),tcold(l),twarm(l),addccp(l)
          write(3,102)l,gdd(l),gsdri(l),m4dri(l),gsins(l),
     %                 m4ins(l),tcold(l),twarm(l),addccp(l)
          write(13,102)l,gdd(l),gsdri(l),m4dri(l),gsins(l),
     %                 m4ins(l),tcold(l),twarm(l),addccp(l)


          do k=1,NTAX
*             write (sysout,103) mutmx(k,l),sapres(k,l),tftmx(k,l)
              write (3,108)mutmx(k,l),sapres(k,l),tftmx(k,l)
              write (12,103)l,k,mutmx(k,l),sapres(k,l),tftmx(k,l)
          enddo

* TLS deleted code for initializing last and next month values
* these are only needed for daily interpolations when using monthly data

        enddo ! l=1,(ntim*tim)-1

*DTP    pause 'Press RETURN to continue.'
c        return


c 900    close(unit=10)          ! premature end of file. Close and reopen
C       open(10,file='climate.inp',status='old',shared,readonly)
c       open(10,file='climate.inp',status='old')
*        read(10,*,err=999,end=999) stname  ! read station name again
c       read(10,*,err=999,end=999) linein  ! read station name again
c       read(10,*,err=999,end=999) linein  ! read station name again
c       goto 910                 ! continue from where eof occurred

  999   write(sysout,200)
        write(3,200)
*DTP    pause 'Press RETURN to quit.'
```

```
      stop 'Forska ENVIRO-D terminated because of read error(s).'

* format statements
  100 format(x,/'Site environmental data input to model'//)
  101 format(' year    gdd     gsdri   -4dri   gsins    ',
     >       'm4ins   tcold   twarm   addCO2'/)
  102 format(x,i4,x,f7.1,2x,f7.4,x,f7.4,x,f7.2,x,f7.2,x,f7.2,
     %       x,f7.2,x,f7.2)
  103 format(x,i4,2x,i2,2x,f7.4,2x,f7.4,2x,f7.4)
  108 format(x,f7.4,2x,f7.4,2x,f7.4)
  104 format(1x,4f6.2)
  105 FORMAT(' year  species  mutmx  sapres  tftmx'/)
  200 format(/' Error in reading environmental data')

* initialize VAX/VMS screen display

C       call init_disp(ib,is,it,ist,ih_a,ih_b,i_a,i_b,iyr,i1,i2)

*DTP  PAUSE 'Forska ENVIRO-D normal termination. Press RETURN to quit.'
      WRITE(SYSOUT,2)
      STOP ' '

* format statements:

2     FORMAT(/' ** ENVIRO-D - Normal Termination **')
      END

*****************************************************************

      SUBROUTINE ENVSUB(sysout,Lat,tran,temp,prec,clou,L,lDSM,yrno)

      implicit none

      INCLUDE 'compar.h'    ! TLS moved global model parameters

       integer year,sysout
      parameter (year=365)

* originally written by Wolfgang Cramer
* substantially amended for use in FORSKA2 - CLIMATE and LANDSCAPE versions
* by Colin Prentice and Martin Sykes 1990
* FURTHER AMENDED TO INCLUDE NEW EVAPO ROUTINE SEPTEMBER 1991 Martin Sykes
* Later temporary fix for insolation, minor health warning December 1991
* Martin Sykes, Uppsala.

* annual environmental indices
*
* gdd    - growing degress days  - site
* gsdri  - growing season drought index - site
* m4dri  - -4 oC drought index - site
* gsins  - growing season average light intensity - site (dpar)
* m4ins  - -4 oC season average light intensity - site   (dpar)
```

```
* sapres - sapwood respiration - species specific - (old del)
* tftmx  - thermal multiplier - species specific

      REAL*4 gdd(maxtim),gsdri(maxtim),m4dri(maxtim),gsins(maxtim),
     %     m4ins(maxtim),tcold(maxtim),twarm(maxtim),addccp(maxtim),
     %     mutmx(maxspe,maxtim),sapres(maxspe,maxtim),
     &     tftmx(maxspe,maxtim)
      integer yr(maxtim)
      common /climo/gdd,gsdri,m4dri,gsins,m4ins,tcold,twarm,addccp,yr,
     %              mutmx,sapres,tftmx


* common for model parameters

      integer npat,ntim,ntax,tim,timret,gamma
      REAL*4    kco,pat,vinc,dbh0,rho,tref,fco2
      common /model/kco,npat,ntim,pat,tim,ntax,vinc,dbh0,rho,tref,
     %        fco2,timret,gamma

* common for site parameters

      REAL*4 wmx,watc
      common /site/ wmx,watc

* common for species parameters

      REAL*4    hmx(maxspe),hds(maxspe),alp(maxspe),lcp(maxspe),
     +        gsc(maxspe),est(maxspe),tdi(maxspe),umn(maxspe),
     +        umx(maxspe),spr(maxspe),smn(maxspe),
     +        lac(maxspe),laf(maxspe),gop(maxspe),
     +        bcf(maxspe),r(maxspe),q10(maxspe),tmin(maxspe),
     +        tmax(maxspe),ccp(maxspe),
     +        dri(maxspe),pro(maxpat,maxspe),mingdd(maxspe),
     +        mintc(maxspe),maxtc(maxspe),mintw(maxspe)
      integer dore(maxspe)
      common /taxa/hmx,hds,alp,lcp,gsc,est,tdi,umn,umx,spr,smn,
     +                 lac,laf,gop,bcf,r,q10,tmin,tmax,ccp,
     %                 pro,dri,mingdd,mintc,maxtc,mintw,dore

*DTP common for annual totals for water balance terms
      REAL*4 totsol,totnet,totppt,totpet,totaet,totrno
      COMMON /YRTOTS/totsol,totnet,totppt,totpet,totaet,totrno

* local variables

      integer days(12),dn,ind,j,k,l,runc,sta,m4day,gdday

      REAL*4 clou(365),dsm(365),prec(365),temp(365),tran(365),
     >mtc(12),mtr(12),mpr(12),mcl(12),mpet(12),ppr(12),
     > dpar,SWP,GLOBAL,NETRAD,
     >alb,cw,dpet,eccen,lat,    ! lsm,
     >solc,spl,ysm,daet,drno,foudpt,foudae,tgsdpt,tgsdae,
```

```
     %          tgsins,tm4ins,gs_swc,m4_swc,gs_swp,m4_swp !  dry

      integer out, yrno
      REAL*4 eps,lDSM

      parameter(out=11,eps=1.0)  ! DTP 95-10-02 Changed eps from 1.0
      parameter(ind=10,sta=14,alb=0.17,solc=1360.,eccen=0.01675)

C DTP ** eccen is the orbital eccentricity used to adjust
C         solar constant for orbital position of Earth888

      data days/31,28,31,30,31,30,31,31,30,31,30,31/

      cw=1.05   ! Initialise soil water supply constant to max at start
                ! of each year's simulation

* make daily arrays of things we have !TLS not used when daily data is input

*     call daily(mtc,lmtc,nmtc,temp)
*     call daily(mtr,lmtr,nmtr,tran)
*     call daily(ppr,lppr,nppr,prec)
*     call daily(mcl,lmcl,nmcl,clou)

        call thermal(sysout,temp,1)

* Initialise daynumber and yearly totals to end of last year's
      dsm(1)=ldsm    ! TLS WATC in year one
      runc=1

* jump back here on rerun (if soil moisture at end of year is less than
* 33% of its water holding capacity (WATC), using decreased value of cw
  511 dn=0
*     rno=0.
      foudpt=0.
      foudae=0.
      tgsdpt=0.
      tgsdae=0.
      m4day=0
      gdday=0
      tm4ins=0.0
      tgsins=0.0
      gs_swc=0.0
      m4_swc=0.0
      gs_swp=0.0
      m4_swp=0.0
      gdd(1)=0.0

      totppt=0.0      ! Initialise annual totals for checking purposes
      totpet=0.0
      totaet=0.0
      totrno=0.0      ! This is not strictly needed, but what the heck
      totsol=0.0
```

```
      totnet=0.0


* ------------------- start daily calculation loop --------------------

        do k=1,365
          dn=dn+1

c store yesterday's soil moisture, jan 2 from dec 31, otherwise
c ysm is ldsm is initialized to watc above
        if(dn.gt.1) then
          ysm=dsm(dn-1)
        else
          ysm=lDSM
        endif

c calculate supply as function of yesterday's soil moisture and maximum rate
c of evapotranspiration
        if(watc.eq.0) then
          spl=0.
        else
          spl=cw*(ysm/watc)
        endif

c call evapo to estimate this day's aet and pet from temperature, cloudiness,
c date, latitude and supply
*        call evapo(alb,eccen,solc,lat,temp(dn),
*     %             clou(dn),dn,spl,daet,dpet,dpar,NETRAD)

        call EVAPO3(alb,eccen,solc,lat,temp(dn),clou(dn),dn,prec(dn),
     >            spl,ysm,SWP,daet,dpet,dpar,tran(dn),GLOBAL,NETRAD)

        SWP=SWP*0.001  ! Convert soil water potential to MPa

* the soil receives today's amount of rain and it loses today's amount of
* "actual" evapotranspiration

        dsm(dn)=ysm+prec(dn)-daet

c take away any excess water as runoff -- adjust for bucket size
        drno=0.0
        if(dsm(dn).gt.watc) then
           drno=(dsm(dn)-watc)
           dsm(dn)=watc
        else
           if(dsm(dn).lt.0) dsm(dn)=0.0
        endif

* DTP - I added this write statement to diagnose output from EVAPO and EVAPO3
************************************************************************
* DTP 99/06/24: Changed these for Pingree Park Experiment
        IF(((L.GE.591).AND.(L.LE.600)).OR.
```

```
     >     ((L.GE.1191).AND.(L.LE.1200))) THEN

*           IF((L.GE.591).AND.(L.LE.600)) THEN
*               write(4,502) dn+(L-591)*365, prec(dn),
*     >                      daet, dpet, dsm(dn), -SWP
*           ELSE IF ((L.GE.1191).AND.(L.LE.1200)) THEN

            IF ((L.GE.1191).AND.(L.LE.1200)) THEN
               write(4,502) dn+(L-1191)*365, prec(dn),
     >                      daet, dpet, dsm(dn), -SWP
          ENDIF
  502   format(I5,'\t',F8.3,'\t',F8.3,'\t',F8.3,'\t',F8.3,'\t',F8.3)

*          write(4,998) dn,dpar,temp(dn),spl,dsm(dn),GLOBAL,NETRAD,
*     >                 daet,dpet,prec(dn),drno
          totppt=totppt+prec(dn)    ! check on yearly totals
          totpet=totpet+dpet
          totaet=totaet+daet
          totrno=totrno+drno
          totnet=totnet+NETRAD
          totsol=totsol+GLOBAL
        ENDIF
  998   format(I3,10(',',f8.3))

*************************************************************************

* sum up annual values

* is this a growing season day or a -4 day ?
* if so then add to growing days and excess temp to gdd total for year
* also total dpet,daet and dpar for both growing season and -4 season
* total daily light intensity over each season

        if(temp(dn).ge.-4.0)then
c         m4day=m4day+1
          foudpt=foudpt+dpet
          foudae=foudae+daet
          tm4ins=tm4ins+dpar

          m4_swc=m4_swc+dsm(dn)    !  add today's soil water content
          m4_swp=m4_swp+SWP        !  add today's soil water potential
        endif

* Here is the temporary fix (MTS)
****************** do a fix for dpar with days greater than 7.5 for GS

        if(temp(dn).ge.7.5)then
         gdday=gdday+1
        endif
****************** do dpar fix with days greater than 4 for -4 season

        if(temp(dn).ge.4.0)then
```

```
          m4day=m4day+1
        endif
****************** END OF 'TEMPORARY FIX' *****************

        if(temp(dn).ge.tref) then
c         gdday=gdday+1
          gdd(l)=gdd(l)+(temp(dn)-tref)
          tgsdpt=tgsdpt+dpet
          tgsdae=tgsdae+daet
          tgsins=tgsins+dpar

          gs_swc=gs_swc+dsm(dn)   ! add today's soil water content
          gs_swp=gs_swp+SWP       ! add today's soil water potential
        endif

*       yrno = rno

        enddo ! k=1,days(j)

* -------------------- end of daily loop ------------------------------


* work out drought index for both growing season and -4 season
* average daily light intensity for both seasons

* DTP. I don't really like this. Surely the point is that species able to
* survive and grow at lower temperatures will have a competitive advantage?
* But if GSINS and M4INS are calculated as the AVERAGE total insolation for
* the respective growing seasons, then FORSKA will generally favour the species
* able only to grow in warmer temperatures (since they will usually get a
* higher AVERAGE growing season insolation). The only exception to this would
* occur when the warmest months are particularly cloudy.

* An alternative and perhaps more logical approach would be to use the TOTAL
* growing season insolation as the driver. This at least would guarantee that
* real differences would be preserved.

*     write (*, 119) tgsdpt,tgsdae,foudpt,foudae
 119  format ('tgsdpt: ', F8.3,'  tgsdae: ', F8.3,
     >         '  foudpt: ', F8.3, '  foudae: ', F8.3)

*      gsdri(l)=(tgsdpt-tgsdae)/tgsdpt
*      m4dri(l)=(foudpt-foudae)/foudpt

* DTP The following is my attempt to make seasonal drought stress dependent
*     upon simulated soil water deficits, calculated from integrated soil water
*     potential. This has the advantage that it is a "REAL*4" effect and should
*     be easily validated against REAL*4 data......
*     Note that gs_swp and m4_swp are negative quantities, so need to be
*     multiplied by -1. (Might be possible to avoid this with a better Psi(Theta)
eqn?)
```

```
      gsdri(l)=-2.5*gs_swp/gdday   ! mean +5 growing season soil water potential
      m4dri(l)=-2.0*m4_swp/m4day   ! mean -4 growing season soil water potential

        gsins(l)=tgsins/gdday
      m4ins(l)=tm4ins/m4day

C       gsins(l)=tgsins/gdday    !tls test
C     m4ins(l)=tm4ins/gdday     !tls test

C     write(5,150)l, m4day, gdday

* test for soil moisture replenishment at end of year
       if(dsm(365).lt.(0.33*WATC)) then
        if(runc.gt.10) then
          write(*,1201) dsm(365)
 1201     format(' stability still not reached..:',f8.3)
*         stop 'error'    ! DTP Deleted this 95/09/11
          goto 888        ! Exit from routine instead
        endif
        write(*,120) 0.33*WATC,dsm(365)
 120    format(' no stability yet...:',2f8.3)

        cw = cw * 0.98 ! Reduce cw by 2% for next iteration - if needed
        runc=runc+1
         goto 511
      endif

c convergence achieved, return to main program
 888  lDSM = dsm(365)           ! Update lDSM to last day of current year
      yrno = totrno             ! Update total yearly runoff -- if needed?

 130  format(x,i4,2x,f7.4,2x,f7.4)  !tls
 150  FORMAT(x,i4,2x,i3,2x,i3) !tls
      return
      end   ! envsub

*---------------------------------------------------------------------------*

      SUBROUTINE THERMAL (sysout,dlytem,l)

       implicit none

      INCLUDE 'compar.h'    ! TLS moved global model parameters

     integer year,l,sysout
      parameter (year=365)

* calculates three different thermal multiplier(fx) for use in forska
* for each species


      REAL*4 gdd(maxtim),gsdri(maxtim),m4dri(maxtim),gsins(maxtim),
```

```
     %         m4ins(maxtim),tcold(maxtim),twarm(maxtim),addccp(maxtim),
     %         mutmx(maxspe,maxtim),sapres(maxspe,maxtim),
     %         tftmx(maxspe,maxtim)
      integer yr(maxtim)
      common /climo/gdd,gsdri,m4dri,gsins,m4ins,tcold,twarm,addccp,yr,
     %                   mutmx,sapres,tftmx

*  common for run parameters

      integer npat,ntim,ntax,tim,timret,gamma
      REAL*4    kco,pat,vinc,dbh0,rho,tref,fco2
      common /model/kco,npat,ntim,pat,tim,ntax,vinc,dbh0,rho,tref,fco2,
     %              timret,gamma


*  common for species parameters

      REAL*4    hmx(maxspe),hds(maxspe),alp(maxspe),lcp(maxspe),
     +         gsc(maxspe),est(maxspe),tdi(maxspe),umn(maxspe),
     +         umx(maxspe),spr(maxspe),smn(maxspe),
     +         lac(maxspe),laf(maxspe),gop(maxspe),
     +         bcf(maxspe),r(maxspe),q10(maxspe),tmin(maxspe),
     +         tmax(maxspe),ccp(maxspe),
     +         dri(maxspe),pro(maxpat,maxspe),mingdd(maxspe),
     +         mintc(maxspe),maxtc(maxspe),mintw(maxspe)
      integer dore(maxspe)
      common /taxa/hmx,hds,alp,lcp,gsc,est,tdi,umn,umx,spr,smn,
     +             lac,laf,gop,bcf,r,q10,tmin,tmax,ccp,
     +             pro,dri,mingdd,mintc,maxtc,mintw,dore

      integer out
      parameter (out=11)

      REAL*4 dlytem(year)

*  local variables

      integer j,k
      REAL*4 tft(maxspe),tresft(maxspe)

      do 25 j=1,ntax
        tft(j)=0.0
        tresft(j)=0.0
   25 continue

*  calculate ft values for each day of the year
*  for each species upto number of taxa

      do 50 k=1,ntax
        do 100 j=1,365

*  add up mutmx multiplier
```

```
          tresft(k)=tresft(k)+(q10(k)**((dlytem(j)-tref)*0.1))

* first check to see if deciduous or not

          if(dore(k).eq.0)then

* totalling daily deciduous multipliers for growing season only

            if(dlytem(j).ge.5.0) then

              tft(k)=tft(k)+(4*((dlytem(j)-tmin(k))*(tmax(k)-dlytem(j)))
     %                /(tmin(k)-tmax(k))**2)
              if(tft(k).lt.0.0)tft(k)=0.0

            endif
          else

* must be evergreen so produce daily values
* do not allow below zero
* checks for temperature greater than -4 oC for evergreen species
*

          if(dlytem(j).ge.-4.0)then

            tft(k)=tft(k)+(4*((dlytem(j)-tmin(k))*(tmax(k)-dlytem(j)))
     %              /(tmin(k)-tmax(k))**2)
            if(tft(k).lt.0.0)tft(k)=0.0
          endif
        endif
  100   continue

   50 continue

* make into species and year multipliers by dividing by 365

      do 125 k=1,ntax
        tftmx(k,l)=tft(k)/365
        mutmx(k,l)=tresft(k)/365
  125 continue

* get sapwood respiration for each spp using r and LAC and temp multiplier
* mutmx

      do 130 k=1,ntax
        sapres(k,l)=(mutmx(k,l)*r(k))/lac(k)
  130 continue

      return
      end
```

```
*-----------------------------------------------------------------------------*

      SUBROUTINE EVAPO3(ALBEDO,eccen,solc,LAT,DTC,SKYPCT,DAY,Ppt,SPL,
     >                  DSM,SWP,DAET,DPET,DPAR,DTR,GLOBAL,NETRAD)

C This version grew out of EVAPO2, DTP, June 1993 - Functionally equivalent to
C Prentice, Cramer and Sykes' (PCS) subroutine EVAPO.  Uses daily temperature
C range, DTR, to estimate daily Tmin and Tmax, for estimation of diurnal
C variation in longwave exchange (assuming Ldown is a function of air
temperature)
C and atmospheric vapour pressure as a fixed proportion of saturation at Tmin.
C The daily integration of solar and net radiation is now performed over 24
C hours, using a simple sawtooth function between Tmin (at dawn LST) and Tmax
C at 15:00 LST where LST means "Local Solar Time".

* DTP 27 May 1993.  Fixed mistake in calculation of DPAR.  Previously it
* had been expressed as a straight function of net shortwave, but now
* it is derived from the total downward SW component. This problem
* showed up when I plotted ET for boREAL*4 forest sites and observed a big
* jump in the daily ET at some point in spring, and a smaller decrease
* in the fall.  This turns out to be due to the day when snow "disappears"
* and "reappears" causing a jump in albedo - and is therefore appropriate.
* However, it also caused an observable jump in DPAR which is NOT correct
* (especially since PAR reflected from the ground might be expected to
* enhance rather than decrease the PAR available to foliage).

c NB: requires monthly cloud cover hours as fraction of daylight hours (<1.0)!
c [Uses CLOUDF=0.5*(1.0-SKYPCT/100) ]

c calculates daily evaporation [mm/day] from:
c delta (solar declination angle [deg],
c day (day of year),
c lat (latitude [deg]),
c sat (slope of saturation vapour curve [Pa/deg C]),
c SKYPCT, CLOUDF (clear sky hours percentage (from sunshine hrs/daylength), cloud
fraction),
c gamma (psychrometer constant [Pa/deg C]),
c lambda (latent heat of evaporation [MJ/kg]),
c solc (solar constant [W/m2]),
c albedo (albedo [dimensionless]),
c dtc (daily mean temperature [deg C]),
c DTR (daily mean temperature range (Max-Min) [deg C])
c spl (soil water supply function [mm/day])

* Alpha    Value of P-T Alpha for non-limiting soil moisture
* Alpha1   Alpha' - Alpha corrected for limiting soil moisture

      IMPLICIT NONE

      REAL*4 rads
*      PARAMETER (rads=ATAN(1.0)/45.0)   ! Radians per degree
      PARAMETER (rads=0.017453292)      ! Radians per degree
```

```
      INTEGER day,HR ! ,I
      REAL*4 daet,SKYPCT,CLOUDF,delta,dpet,dtc,eccen,dpar,
     >     gamma,lambda,lat,sat,Esat,Eair,solc,spl,DSM,DTR
      REAL*4 ALPHA,ALPHA1,SpGam,COSDEC,COSLAT,EPSA,EPSAC,
     >     EPSG,ETSRAD,IAET,IPET,NETRAD,ORBITC,SINDEC,
     >     SINLAT,SINPHI,ST,SUNUP,GLOBAL,TK,VD,ALBEDO,ALBED2
      REAL*4 SVP,dSVPdT,SWP,Tsrf,LWup,LWdown,H,Qnet,Rnet,Get_TC
      REAL*4 TNow,Tmin,Tmax,Tice,Tabs,RHair,VDD,Rv,Ra,LEsoil,B
      REAL*4 Ppt                        ! Today's rainfall
      REAL*4 FSOLAR,                    ! Ratio of Q/Qo derived from Boisvert et
al. 1990
     >     SKYFRC

      PARAMETER (ALPHA=1.25) ! (ALPHA=1.00) ! Could make this a vegetation-
specific variable??
      PARAMETER (Tice=273.16)         ! Ice point temperature [K]
      PARAMETER (Rv=4.619E-04)        ! Gas constant for water vapour

* We start with some expressions that will reoccur several times....

* Estimate cloud fraction from hours of sunshine.  Is there an alternative
* approach to this which has a more defensible basis?
* The factor of 0.5 is needed to reduce the overall impact of cloudy days
* I.e. the proportion of hours of sunshine recorded by a Campbell-Stokes
* recorder will generally be smaller than the proportion of clear sky
* averaged over the course of the day (???).  This appears to be the only
* way of significantly boosting the daily input of solar radiation without
* altering fairly well established factors.

      CLOUDF=0.5*(1.0-SKYPCT/100)
*      CLOUDF=1.0-SKYPCT/100

* Estimate today's Tmin and Tmax from the mean and range
      Tmin = dtc-dtr/2
      Tmax = dtc+dtr/2

* Could estimate barometric pressure as function of altitude (m a.s.l.),
* entered as a site variable.  The following linearization is derived
* from data in Weast (1985).  It should be correct within an error less
* than the possible day-to-day variation (+/- 5%).
*     PATM=-0.0098*ALTUDE+101   ! Atmospheric pressure in kPa

* SINLAT and COSLAT are the sine, cosine of the latitude
      SINLAT=sin(lat*rads)
      COSLAT=sqrt(1-SINLAT**2)    ! Avoid use of cosine function
      ORBITC=2*eccen*cos(0.0172025*DAY)

* Next we calculate the extraterrestrial solar, ETSRAD, corrected
* for orbital eccentricity for this day.
      ETSRAD=SOLC*(1+ORBITC)

c DELTA is today's solar declination in degrees
```

```
* This is a slightly optimized version of PCS' original equation -
* which also corrects for orbital eccentricity.
      DELTA=-23.45*COS(0.0172025*(day+10.)+ORBITC)

* SINDEC and COSDEC are the sine and cosine of the solar declination angle
      SINDEC=SIN(DELTA*rads)     ! Must be a better way of getting this
      COSDEC=sqrt(1-SINDEC**2)   ! Avoid extra use of cosine function

* Also get vapor density (from vapour pressure) to estimate atmospheric
* emissivity as a function of moisture content.  From Campbell (1977, 1985)
* following Brutsaert (1975).  (In units of g/m3)
      Eair=SVP(Tmin)                    ! Today's mean vapour pressure [kPa]
      CALL ABSHUM(Tmin,VD,sat)          ! Get today's mean vapour density
                                        ! sat is used here as a dummy variable
      VD=VD*1000                        ! Convert kg/m3 -> g/m3

* Estimate soil water potential from SPL
*       SWP=min(0.0,(SPL-1.5)*5.0)! * 1E+03    ! Soil water potential in J/kg
*DTP 98/09/28  SWP=min(0.0,(SPL-0.5)*5.0) * 1E+03    ! Soil water potential in
J/kg
*DTP 98/09/28: Note that above statement means that SWP is always non-zero.
* (since, SPL <= 1.05.). Is this a problem?

* DTP 98/09/29: Try this one from enviro.f~ ....
      SWP=min(0,-1.5*(SPL**(-5.0)))     ! Soil water potential in J/kg
C  !tls- constants reflect generic sandy loam(see Price 1999)
* ... with these values from soilwat.xls ...
*       SWP=min(0,-2.0*(SPL**-5.5))    ! Soil water potential in J/kg

* Estimate P-T Alpha for this day as function of soil water supply
      ALPHA1=MIN(ALPHA,ALPHA*SPL)     ! Limit Alpha to linear function of soil
water content

* Check for presence of snow cover.  We will assume that if the daily mean air
* temperature is below -1 C, then there is snow cover, and will arbitrarily set
* the albedo to 0.3.  Otherwise, we will use 0.15 for mixed forest (e.g Grace
(1983)).
* But, as Dave Halliwell and Derek Peddle have pointed out, the albedo is often
* quite a bit higher - e.g. lichen or bare soil under pine, pure aspen stands.
Only
* spruce stands will have relatively low albedos (< 0.1). Let's try albedo = 0.2
* in summer. The value of 0.3 in winter is unlikely to have much impact because
* evaporation rates will be low when Tair < -1 C.
* See also review in Dorman and Sellers (1989)

*     write(*,*) dtc, alpha1, albedo
      IF(dtc.LT.-1.0)THEN
*Debugged to here......!
*        ALBEDO = 0.30         ! should be 0.30
         ALBED2 = 0.30
*Terminates here......!
*     write(*,*) dtc, alpha1, albedo
```

```
      ELSE
*        ALBEDO = 0.20           ! should be 0.15
        ALBED2 = 0.20
      ENDIF


* Calculate approximate hour of sunrise on this day.  This occurs
* when elevation angle, PHI, is zero, i.e. SINPHI=0.
* NOTE: The daylength is therefore 2*(12-SUNUP), so we should
* integrate the daytime longwave component over this period too.

      SINPHI=-SINDEC*SINLAT/(COSDEC*COSLAT)
      IF(SINPHI.LT.-1.0)THEN
        SUNUP=12.0                       ! Polar night
      ELSE IF(SINPHI.GT.+1.0)THEN
        SUNUP=0.0                        ! Polar day
      ELSE
        SUNUP=12.0-3.8197*ACOS(SINPHI)   ! "Normal" day (!)
      ENDIF

      SKYFRC=SKYPCT/100          ! Convert SKYPCT to a fraction

* FSOLAR is Boisvert et al (1990) Q/Qo for this day
      FSOLAR = 0.323 + 0.427*SKYFRC - 0.00378*Tmin -
     >         0.0328*(1-SKYFRC)*LOG(1+Ppt) - 0.0798*(1-SKYFRC)**15
* This is a little fudge designed to bring solar radiation estimate into
* line with Canadian Hydrological Atlas data.
      FSOLAR = FSOLAR * 1.065

* Longwave up - assume universal surface emissivity of 0.97 for now
      EpsG=0.97                              ! Campbell (1977) [10.20]

* Estimate atmospheric emissivity, EpsA, using Monteith (1973), equation
* (3.5) who follows Swinbank (1963).  I also tried Campbell (1977), equation
* (5.13) who adapts Idso-Jackson (1969), but there is quite a difference at
* both ends of the range.  I have come to trust JLM!  However, this equation
* goes to zero at low temperatures (i.e. < -20 C).  Using the Brutsaert (1975)
* formula given in Campbell (1977, 1985), would seem to give more stable results.
* (But, it requires daily minimum, and I still find it hard to believe what it
* does for polar longwave balance.)  For now, use Monteith.
*     EpsA=0.72+0.005*DTC                    ! Campbell (1977) [5.13]
*     EpsA=MAX(0.0,1.2-171.0/(5.67E-08*Tabs**4))  ! Monteith (1973) [3.5]
      EpsA=MIN(1.0,0.58*VD**(1/7))           ! Campbell (1977) [5.12]

* Account for emissivity of cloud, EpsAC, estimated following Monteith (1973).
* I looked originally at Campbell (1977), but found that his equation (5.14)
* runs into trouble around 0 C (+/- 8 C).  I tried modifying his expression,
* but then discovered that Monteith's (3.14) has an altogether different
* response (i.e. increasing rate of decrease at low temperatures).  However,
* Campbell (1985) cites Unsworth and Monteith (1975), which appears to (a)
* recognise the limitations with his own equations; and (b) adds strength
* to Monteith's.  My "modified" Campbell looks quite similar to Unsworth
```

```
* and Monteith, when using Monteith's (1973) clear-sky emissivity equation.
*     EpsAC=EpsA+CLOUDF*(1-EpsA-8/DTC)        ! Campbell (1977) [5.14]
*     EpsAC=EpsA*(1-CLOUDF)+CLOUDF            ! My "simplified" version of
Campbell
*     EpsAC=EpsA*(1+N*CLOUDF**2)              ! Monteith (1973) [3.14]
      EpsAC=(1-0.84*CLOUDF)*EpsA+0.84*CLOUDF ! Unsworth & Monteith (1975), (in
                                              ! Campbell (1985), [12.3])
      EpsAC=MIN(EpsAC,1.0)                    ! Guard against the impossible.

      GLOBAL=0.0              ! Initialize global solar total SW radiation
      NETRAD=0.0              ! Initialize daily total for Net radiation
      DPET=0.0                ! Initialize daily totals for PET and AET
      DAET=0.0
      DPAR=0.0                ! and for daily total downward PAR

C     CLOUDF=CLOUDF*0.5       ! Fudge needed to boost SW, without affecting LW

      DO HR = 1,24
        Tnow=GET_TC(Tmin,Tmax,SUNUP,HR)       ! Estimate current air temperature
        Tabs=Tnow+Tice                        ! Convert Tnow to Kelvin
        Esat=SVP(Tnow)                        ! Current saturation vapour pressure
        RHair=Eair/Esat                       ! Current estimated RH (fraction)
        VDD=(Esat-Eair)/(Rv*Tabs)             ! Current saturation vapour density
deficit (g/m3)
        CALL TABLE2(Tnow,gamma,lambda)        ! Current values of gamma, lambda
(Pa/K; kJ/g)
        sat=1000*dsvpdt(Tnow)                 ! Current value of slope of SVP/T
(Pa/K)
        LEsoil=SPL*Lambda/0.0036              ! Soil-limited ET expressed as flux
density (W/m2)

        LWdown=EpsAC*5.67E-08*(Tabs**4)       ! Downward longwave at this hour
(W/m2)

        SINPHI=SINDEC*SINLAT+COSDEC*COSLAT*COS(0.2618*(HR-12.5))
        IF(SINPHI.GT.0.0) THEN                ! OK: Sun above horizon
* Calculate net incident solar radiation from elevation angle, after
* estimating net sky transmissivity following Stull (1988), equation (7.3.1a),
* who cites Burridge and Gadd (1974).  I simplified their equation to
* try to represent "average" absorption for a range of cloud covers at a
* range of altitudes.  The following gives 0.8 at cloudf=0, and 0.1075 at
* cloudf=1.0 I.e.: absorption=0.8925*CLOUDF
*     I.e. CAF = 0.23Cl**2 - 0.885Cl + 0.8 where CAF is the
*           "cloud SW absorption factor", and Cl is the cloud fraction
* Elevation effects on atmospheric absorption have been ignored.
* Could consider decomposing total into beam and diffuse components -
* but we are only trying to estimate daily integrated total anyway.
* NOTE: found 0.61 gave slightly better results than 0.6.
*         TK=(0.61+0.2*SINPHI)*(1-0.8925*CLOUDF)    ! Net sky transmissivity
* Estimate today's atmospheric transmissivity using Bristow and Campbell (1984)
C         B=0.036*exp(-0.154*dtr)             ! Bristow and Campbell's (1984) "B"
```

```
C          TK=0.7*(1-exp(-B*dtr**2.4))        ! We can adjust these coefficients a
bit
C          ST=ETSRAD*TK*SINPHI                ! Total instantaneous downward SW
(W/m2)
           ST=ETSRAD*FSOLAR*SINPHI            ! Total downward SW corrected for
atmospheric absorption
           GLOBAL=GLOBAL+ST                   ! Accumulate downward shortwave
C          write (*,989) FSOLAR,ETSRAD,ST,GLOBAL
C989       FORMAT ('Fsolar = ',F10.3,'  ETSrad = ',F10.3,'  ST = ',F10.3,
C     >         '  CumTot SW = ', F10.3)
         ELSE
           ST=0.0                             ! Sun not up, so no shortwave
         ENDIF

*         Qnet=ST*(1-ALBEDO)+LWdown            ! Net available incoming radiation
         Qnet=ST*(1-ALBED2)+LWdown            ! Net available incoming radiation
         CALL BRISTO(Tnow,RHair,LEsoil,SWP,Qnet,Tsrf,EpsG,
     >              LWup,H,IAET,Rnet,Ra)      ! Solve for Tsrf

         DAET=DAET+IAET                       ! Accumulate actual ET     (mm/d)

* Estimate current net radiation.  Correct for heat storage by assuming 10% of
Rnet
*         Rnet = 0.90*Rnet
         Rnet = ST*0.467 - 25.0               ! Temporary fix from Atlas data
         NETRAD = NETRAD + Rnet               ! Accumulate daily total

* Get (s+gamma) term, multiplied by lambda, for use in ET calculations.
         SpGam = (sat+gamma)*lambda

* Estimate current equilibrium evaporation rate from Priestley and Taylor (1972).
* Convert from W/m2 to MJ/m2/hr to get the result in mm/hr
         IPET=0.0036*sat*Rnet/SpGam           ! Eeq = (Rn-G)s/(s+gamma) ; Eeq > 0
* Estimate current potential evaporation rate from Penman (or P-M?) equation
*        IPET=MAX(IPET,0)+3.6*gamma*VDD/(40.0*(sat+gamma))  ! Ep = Penman PET
         IPET = IPET*ALPHA
         DPET=DPET+IPET                       ! Accumulate potential ET  (mm/d)
       ENDDO

       DPET=max(0,DPET)                       ! don't allow negative DPET

* Convert daily totals from W/m2 to MJ/(m2 d)
       GLOBAL=GLOBAL*0.0036                   ! Total downward shortwave
(MJ/m2/day)
       NETRAD=NETRAD*0.0036                   ! Convert to daily net radiation -

       DAET=min(DAET,DPET*ALPHA1/ALPHA)       ! don't allow AET to exceed soil-
limited PET
       DAET=max(0,DAET)                       ! don't allow negative AET

* Estimate daily above-canopy PAR total using value derived from Meek (1984)
```

```
      DPAR=GLOBAL*2.1                        ! Total downward daily DPAR
(Mole/m2/day)
* Convert DPAR to mean daily flux
*     DPAR=DPAR*(1E+03)/(3.6*2*(12.0-SUNUP)) ! Average daytime PAR (uMole/m2/s)
      DPAR=DPAR*(1E+03)/(3.6*24)             ! 24-hour average PAR (uMole/m2/s)

      END                                    ! EVAPO3

************************************************************************

      SUBROUTINE BRISTO (Tair,RHair,LEsoil,SWP,Q,Tsurf,EpsG,
     >                   LWup,H,AET,Rnet,Ra)

* Bristow's (1987) approach for solving the surface energy balance
* equation (SEBE) to get surface temperature using Newton's iterative
* method.  Returns estimates of upward longwave, sensible heat flux,
* net radiation (all in W/m2) and actual ET (in mm/hr).

* Coded by DTP, 2 June 1993.

      IMPLICIT NONE

      REAL*4 Tair,Tsurf,RHair,SWP,Q,EpsG,LWup,H,AET,Rnet
      REAL*4 Ke,Kc,Ra,Gamma,Lambda,LEsoil


*     PARAMETER (Ra = 40.0)              ! "Mean" aerodynamic resistance [s/m]
*     PARAMETER (Kc = 10.0)              ! Heat transfer coefficient [W/m2]
*     PARAMETER (Ke = 0.005)             ! Aerodynamic conductance for vapour
[m/s]

      Ra = 30.0 ! 20.0, 500.0, 40.0      ! Aerodynamic resistance [s/m]
      Ke = 1/Ra                          ! Conductance for water vapour [=0.025
m/s]
      Kc = Ke*1200                       ! Heat transfer coefficient [= 30 W/m2]

      CALL NEWTON (Q,Tair,LEsoil,SWP,Kc,Ke,RHair,EpsG,LWup,H,AET,Tsurf)

      Rnet = Q - LWup                    ! Instantaneous net radiation

      CALL TABLE2(Tsurf,Gamma,Lambda)    ! Get Lambda at new Tsurf
      AET = AET*0.0036/Lambda            ! Get current AET from LE (W/m2 ->
mm/hr)

      RETURN
      END                                !  SolveSurfaceTemperature

*********************************************************************************
****

      REAL*4 FUNCTION GET_TC (Tmin,Tmax,SunUp,Hour)
```

```
* Estimates temperature at time Hour, as a linear function of the time between
* SunUp (Tmin) and 15:00 LST (Tmax).  If SunUp < Hour < 15:00 then T(Hour) is
* increasing with time; otherwise it is decreasing.

      IMPLICIT NONE

      REAL*4 Tmin,Tmax,SunUp
      INTEGER Hour

      IF(Hour.LE.SunUp) THEN                         ! before dawn
        GET_TC = Tmax - (Tmax-Tmin) * (9+Hour)/(9+SunUp)
      ELSEIF(Hour.GE.15.0) THEN                      ! after 15:00 LST
        GET_TC = Tmax - (Tmax-Tmin) * (Hour-15)/(9+SunUp)
      ELSE                                           ! between dawn and 15:00 LST
        GET_TC = Tmax - (Tmax-Tmin) * (15-Hour)/(15-SunUp)
      ENDIF

      RETURN
      END

************************************************************************************
****

      REAL*4 FUNCTION SVP(T)

* D.T. Price. 29 November 1989 ff.

* Using temperature in deg. C as argument, returns saturation vapour
* pressure over water or ice in kPa, using Lowe's (1977) sixth order
* polynomial approximation.  When compared to the Brooker (1968) model
* used earlier, the overall difference with one test data set was an
* increase in calculated PET of 0.1 mm during the year!  But at least
* it's faster!
* Reference:  Lowe, P.R. 1977.  An approximating polynomial for
*             computation of saturation vapor pressure.
*             J. Appl. Meteorol. 16:100-103.

* Declare constants.
* W0-W6 are constants for Esat over water
* I0-I6 are for Esat over ice (at T < 0 C)

c     REAL*4 SVP,T
      REAL*4 W0,W1,W2,W3,W4,W5,W6
      REAL*4 I0,I1,I2,I3,I4,I5,I6

* Assign values to constants
      PARAMETER (W0 = 6.107799961E-01)
      PARAMETER (W1 = 4.436518521E-02)
      PARAMETER (W2 = 1.428945805E-03)
      PARAMETER (W3 = 2.650648471E-05)
      PARAMETER (W4 = 3.031240396E-07)
      PARAMETER (W5 = 2.034080948E-09)
```

```
      PARAMETER (W6 = 6.136820929E-12)

      PARAMETER (I0 = 6.109177956E-01)
      PARAMETER (I1 = 5.034698970E-02)
      PARAMETER (I2 = 1.886013408E-03)
      PARAMETER (I3 = 4.176223716E-05)
      PARAMETER (I4 = 5.824720280E-07)
      PARAMETER (I5 = 4.838803174E-09)
      PARAMETER (I6 = 1.838826904E-11)

*  If T is above the ice-point temperature, then calculate SVP for
*  liquid water, otherwise calculate it for ice.

      IF(T.GE.0.) THEN
        SVP=W0 + T*(W1 + T*(W2 + T*(W3 + T*(W4 + T*(W5 + T*W6)))))
      ELSE
        SVP=I0 + T*(I1 + T*(I2 + T*(I3 + T*(I4 + T*(I5 + T*I6)))))
      ENDIF
      RETURN
      END

************************************************************************

      REAL*4 FUNCTION DSVPDT(T)

* D.T. Price. 16 December 1989 ff.

* Using temperature in deg. C as argument, returns derivative (s) of
* the saturation vapour pressure WRT temperature over water or ice in
* kPa/(deg C), using Lowe's (1977) sixth order polynomial approximation.

* Reference:  Lowe, P.R. 1977.  An approximating polynomial for
*             computation of saturation vapor pressure.
*             J. Appl. Meteorol. 16:100-103.

      REAL*4 T  ! TLS deleted DVSPDT

* Declare constants.
* W0-W6 are constants for dEsat/dT over water
* I0-I6 are for dEsat/dT over ice (at T < 0 C)

      REAL*4 W0,W1,W2,W3,W4,W5,W6
      REAL*4 I0,I1,I2,I3,I4,I5,I6

* Assign values to constants
      PARAMETER (W0 = 4.438099984E-02)
      PARAMETER (W1 = 2.857002636E-03)
      PARAMETER (W2 = 7.938054040E-05)
      PARAMETER (W3 = 1.215215065E-06)
      PARAMETER (W4 = 1.036561403E-08)
      PARAMETER (W5 = 3.532421810E-11)
      PARAMETER (W6 =-7.090244804E-14)
```

```
      PARAMETER (I0 = 5.030305237E-02)
      PARAMETER (I1 = 3.773255020E-03)
      PARAMETER (I2 = 1.267995369E-04)
      PARAMETER (I3 = 2.477563108E-06)
      PARAMETER (I4 = 3.005693132E-08)
      PARAMETER (I5 = 2.158542548E-10)
      PARAMETER (I6 = 7.131097725E-13)

*  If T is above the ice-point temperature, then calculate DSVPDT for
*  liquid water, otherwise calculate it for ice.

      IF(T.GE.0.0) THEN
        DSVPDT=W0 + T*(W1 + T*(W2 + T*(W3 + T*(W4 + T*(W5 + T*W6)))))
      ELSE
        DSVPDT=I0 + T*(I1 + T*(I2 + T*(I3 + T*(I4 + T*(I5 + T*I6)))))
      ENDIF
      RETURN
      END

C ************************************************************************

      SUBROUTINE ABSHUM (T, SVD, DSVDDT)      ! Bristow's FUNCTIONS G, H

* Returns saturation vapour density, SVD (kg/m3) at T (C), using SVP(T)
* (kPa) and slope of saturation vapour density curve at T (C), using
* DSVPDT(T) (kPa/K), in DSVDDT

      REAL*4 T,Tabs,SVD,DSVDDT,H1,Tice
      REAL*4 SVP,DSVPDT

      PARAMETER (H1=2.166)              ! MW of water/Gas Constant [g K/J]
      PARAMETER (Tice = 273.16)         ! Ice point temperature, K

      Tabs = T + Tice
      SVD = H1 * SVP(T)/Tabs
      DSVDDT = (-SVD + H1 * DSVPDT(T))/Tabs

      RETURN
      END

*-------------------------------------------------------------------------

      SUBROUTINE SRFHUM (SWP,T,RHS,dRHSdT)    ! Bristow's FUNCTIONS I, J

* Returns relative humidity at soil surface (RHS) [fraction], and the
* derivative of RHS wrt T as function of soil water potential, SWP [MPa],
* and surface temperature, T (C).

      REAL*4 SWP,T,RHS,dRHSdT,SH1,Tice,Tabs,Arg

      PARAMETER (SH1=0.002166)     ! MW of water/Gas Constant [kg K/J]
```

```
      PARAMETER (Tice=273.16)       ! Ice point temperature, K

      Tabs = T + Tice               ! Convert to Kelvin
      Arg = SWP * SH1/Tabs          ! Arg is (SWP Mw)/(R T)
      RHS = exp(Arg)
      dRHSdT = RHS * (-Arg/Tabs)
      RETURN
      END

*-------------------------------------------------------------------------

      REAL*4 FUNCTION KAPPA (Lambda,DLamDT,RHS,dRHSDT,SVD,dSVDDT)   ! Bristow's
FUNCTION K

* Evaluates Bristow's (1987) function K - collection of derivative terms

      REAL*4 Lambda,dLamdT,RHS,dRHSdT,SVD,dSVDdT

      KAPPA=(Lambda*RHS*dSVDdT)+(Lambda*SVD*dRHSdT)+(RHS*SVD*DLamDT)

      RETURN
      END                              ! Kappa

*-------------------------------------------------------------------------

      SUBROUTINE NEWTON (Q,Tair,LEsoil,SWP,Kc,Ke,RHair,EpsG,
     >                   LWup,H,LE,Tsurf)

* Solves SEBE for Tsurf given values for Q, Tair, SWP, Kc, Ke and RHair

      IMPLICIT NONE

      REAL*4 Q,Tair,LEsoil,SWP,Kc,Ke,RHair,EpsG,LWup,H,LE,Tsurf
      REAL*4 F,dFdT,Tabs,Tabs2,dLWdT,K,SB,Gamma,Lambda
      REAL*4 RHS,dRHSdT,SVD,dSVDdT,SSVD,dSSVdT,VDair
      REAL*4 Ttol,Tice,dLamdT,Kappa

      INTEGER SYSOUT,Count

      PARAMETER (SYSOUT=6)
      PARAMETER (Ttol = 0.5)             ! Tolerance in SEBE of 0.5 W/m2
      PARAMETER (Tice = 273.16)          ! Ice point temperature, K
      PARAMETER (dLamdT=-2.38E+03)       ! Bristow's FUNCTION F, J/kg
      PARAMETER (SB=5.6697E-08)          ! Stephan-Boltzmann constant [W/(m2 K)]

      CALL ABSHUM (Tair, SVD, dSVDdT)    ! SVD contains Satn Vap. Density at Tair
      VDair = RHair*SVD                  ! Atmospheric vapour density

      IF(SWP.LE.-1E+06) THEN             ! Assume soil is completely dry
        SWP = -1.0E+06
        RHS = 0.0
        dRHSdT = 0.0
```

```
        SSVD = 0.0
        dSSVdT = 0.0
        LE = 0.0
      ENDIF

      Tsurf = 25.0                       ! Start with "average surface
temperature"
      Count = 0                          ! Initialise iteration counter
      F = 100.0                          ! Initialise F to some large value
      dFdT = 20.0                        ! Initialise Fprime

      DO COUNT=0,100
        Tabs = Tsurf + Tice
        CALL TABLE2 (Tsurf, Gamma, Lambda)
        Lambda = Lambda * 1E+06                   ! Convert to J/kg

        IF(SWP.GT.-1.0E+06) THEN                  ! Do new soil humidity
calculations
          CALL ABSHUM (Tsurf, SSVD, dSSVdT)       ! SSVD = Satn Vap Density at
Tsurf.
          CALL SRFHUM (SWP, Tsurf, RHS, dRHSdT)   ! RH, dRH/dT at soil surface
          LE=min(LEsoil,Lambda*Ke*(RHS*SSVD-VDair))! Latent heat flux - subject
to soil-
                                                  ! limited rate of water supply
        ENDIF

        Tabs2 = Tabs**2
        LWup = EpsG * SB * Tabs2**2               ! Upward longwave
        H = Kc * (Tsurf - Tair)                   ! Sensible heat flux
        F = LWup - Q + H + LE                     ! Get surface temperature error
from SEBE

*       WRITE (SYSOUT,100) Count,F,dFdT           ! Commented out to save paper
and time!!
  100   FORMAT ('Iteration ', I2, ':  F = ', F10.5, '  dF/dT = ', F10.5)
        IF(ABS(F).LE.Ttol) GOTO 999               ! Closure achieved

        dLWdT = 4*EpsG * SB * Tabs * Tabs2
        K = Ke*(Kappa(Lambda,dLamdT,RHS,dRHSdT,SVD,dSVDdT) -
     >                VDair*dLamdT)
        dFdT = dLWdT + Kc + K                     ! Get derivative of F

        Tsurf = Tsurf - F/dFdT                    ! Get new estimate of Tsurf
      ENDDO

  999 RETURN
      END                                         ! SUBROUTINE NEWTON

****************************************************************************

      SUBROUTINE TABLE2 (tc,gamma,lambda)
```

```
C DTP Returns values of gamma (psychrometric constant, Pa/deg C) and lambda
C     (latent heat of evaporation, kJ/g) for temperature tc, in Celsius.
C     This replaces subroutine TABLE.  It does the same thing, but it is
C     explicit, and more accurate for intermediate temperatures.  Should be
C     faster than the looping approach used in TABLE.  The data come from
C     Jones (1983).

      REAL*4 tc,gamma,lambda
      REAL*4 gamref,gamcor,lamref,lamcor,lamfus
      data gamref/64.9/           ! approx value for gamma at 0 C and 100 kPa
      data gamcor/0.0633/         ! temperature lineariz'n factor for gamma
      data lamref/2.501/          ! latent heat of evap at 0 C (kJ/g)
      data lamcor/-0.00238/       ! temperature lineariz'n factor for lambda
      data lamfus/0.335/          ! approximate heat of fusion of ice (kJ/g)

      gamma=(gamref + (tc * gamcor)) ! could make this pressure dependent too

      if(tc.lt.0) then
        lambda=lamfus + lamref + (tc * lamcor)
      else
        lambda=lamref + (tc * lamcor)
      endif

      end
*********************************************************************
```

PROGRAM FORSKA2V+

```
        IMPLICIT NONE
*
* FORSKAC - 2L - LANDSCAPE version 1990

* Model to simulate the dynamics of forest stand composition and
* structure. Version 1.1 created August 1988 by Colin Prentice and
* Rik Leemans, Institute of Ecological Botany, Uppsala University,
* Box 559, S-751 22 Uppsala, Sweden
*
* Version 2L amended to include climate and disturbance
* by Colin Prentice and Martin Sykes  Uppsala 1990

* DTP Alterations to original code added by Dave Price are marked with
* my initials (as here). Also, some modifications have been added by Sean
* Sampson, marked 'SS'.

* DTP 23 November 1995. Revisions added to "normal" version in
* forska2n.f which makes this version the "variable" version, forska2v.f.

* TLS August 2006. Revisions added to "monthly variable" version
* forska2v.f to make "daily variable" version forska2v+.f, including
```

```
* a number of fixes and modifications marked with TLS.

* The normal version is essentially the model provided by Martin Sykes,
* with fixes and mods. to display more data, but not change any algorithms.
* The variable version features modifications to run the model with
* variable climate data rather than climate normals. (Get it?)
* TLS Forska2v+ is designed to run also with variable daily climate data.

c on UNIX, compile with "f77 -u" - to warn of undeclared variables

*DTP 21 October 1998.
*    Changed Model configuration to allow more trees per plot. This has to be
*    fixed in all COMMON blocks. Put COMMONs into compar.h include files so
*    that these can be modified conveniently.
* TLS complots.h modified to include variable PDENS (now called complot.h).

      INCLUDE 'compar.h'    ! global model parameters
      INCLUDE 'comrun.h'    ! settings for this run
      INCLUDE 'comsite.h'   ! site and climate variables
      INCLUDE 'comtax.h'    ! species parameters
      INCLUDE 'comnames.h'  ! species names
      INCLUDE 'comtree.h'   ! tree parameters
      INCLUDE 'comdead.h'   ! dead tree parameters
      INCLUDE 'complot.h'  ! plot output parameters

* local variables

      INTEGER L,J,INIT,IOUT,PTCAGE(MAXPAT),SYSOUT,SYSIN,
     >        DSINT(MAXDSI),DISNUM(MAXPAT),DHIST(MAXPAT,MAXDIS)

* input and output devices for VAX/VMS and IBM/PC-AT
      PARAMETER(SYSOUT=6,SYSIN=5)

* input and output devices for Macintosh (Absoft or Microsoft Fortran Compiler)
C     PARAMETER(SYSOUT=9,SYSIN=9)

* reading or initializing parameters

      CALL LGTMOD(SYSOUT,SYSIN)
      CALL CGTSPE(SYSOUT,NTAX)
      CALL CGTOUT(SYSOUT,NTIM,TIM,INIT,IOUT,NTAX)

* reads in basic CLIMATE data to be worked on to produce gdd etc.
* call to bucket and environmental routines

        CALL GETPRO(SYSOUT)

* TLS Deleted call to GT_ENV to read in raw climate data (when SWCLIM.EQ.0).
* Forska2V+ uses exclusively processed climate data from enviro*.inp.

* continues reading or initialising parameters
```

```
      CALL CGTRAN()

* initialize VAX/VMS screen display

C       call init_disp(ib,is,it,ist,ih_a,ih_b,i_a,i_b,iyr,i1,i2)


* DTP Initialise array DSINT which maintains a record of the disturbance
intervals
*     created during the simulation
      DO J=1,MAXDSI
         DSINT(J)=0
      ENDDO

* DTP Initialise arrays DHIST and DISNUM which maintain records of the history
*     of disturbances. DISNUM records the 'number' of the last disturbance since
*     start of simulation, for each patch. DHIST records the timesteps at which
*     each disturbance occurred, for each patch.
      DO J=1,MAXPAT
        DO L=1,MAXDIS
          DHIST(J,L)=0
        ENDDO
      ENDDO

* DTP Initialise array PPROD which stores previous values of PBIOM for
* productivity calculations
      DO L=1,NPAT
        DO J=1,NTAX
          PPROD(L,J) = 0.0          ! Total Productivity for plot L, sp. J
        ENDDO
      ENDDO
      DO J=1,NTAX
        DO L=1,MAXACL+1
          PBIOM1(J,L) = 0.0         ! Total biomass for sp. J, ageclass I
          PPROD1(J,L) = 0.0         ! Total productivity for sp. J, ageclass I
          PBASA1(J,L) = 0.0         ! Total basal area for sp. J, ageclass I
          PLAI1(J,L) = 0.0          ! Total LAI for sp. J, ageclass I
          PDENS1(J,L) = 0           ! Total stem density for sp. J, ageclass I
        ENDDO
      ENDDO

* Simulation proceeds with successive calls to subroutines for establishment
* (ETBL) and growth (TVXT). TVXT calls MORT to determine mortality, also
* checks to see if a patch has been wiped out if so flags all trees in that
* patch. SKOT then eliminates any trees that have been flagged for removal,
* and sprouts those dead trees that are capable of resprouting.
* A stand description is written every LPR timesteps

      DO 200 L=1,NTIM

* Following code randomises order of climate records. It is a quick temporary
fix.
```

```
*         IF((L.GE.1).AND.(L.LE.800))THEN  ! randomise from years 1-800
*           M=RAND()*800
*         ELSE IF((L.GE.801).AND.(L.LE.900))THEN ! randomise years 801-900
*           M=RAND()*100 + 800
*         ELSE                                   ! randomise years 901-1800
*           M=RAND()*900 + 900
*         ENDIF

* calls climate effect routines
          CALL CLIMEF(SYSOUT,L)
*          CALL CLIMEF(SYSOUT,M)                 ! use this when randomising
climate record

* check to see if first year - if so then call CINIT routine which
* initialises INC,PRO,GOP and NUM

          IF(L.EQ.1)THEN
             CALL CINIT(NUM)

* optionally reads in state description

             IF(INIT.NE.0)THEN
               CALL IN(SYSOUT,NPAT,PTCAGE)
               CALL CSTAND(SYSOUT,L,BCF,HMX,HDS,PRO,DORE,PTCAGE)
                  ENDIF
             ENDIF

* TLS Initialise DISNUM to maintain a record of the number of disturbances
* on each patch during the simulation.

        DO 199 J=1, NPAT   !TLS added to initialize DISNUM
           DISNUM(J)=0.0
199     CONTINUE

         DO 201 J=1,NPAT
*DTP          WRITE(SYSOUT,1)J,L*TIM
                CALL CETBL(J,L,SYSOUT,PTCAGE)
                  CALL LTVXT(SYSOUT,J,L,PTCAGE,DSINT,DHIST,DISNUM)
*             CALL CETBL(J,M,SYSOUT,PTCAGE)
*             CALL LTVXT(SYSOUT,J,M,PTCAGE,DSINT,DHIST,DISNUM)
              CALL CSKOT(J,DBH0)
201      CONTINUE

* write and update stand descriptions

C       if(ib.eq.1)call upd_disp(l,is,it,ist,ih_a,ih_b,i_a,i_b,iyr,i1,i2)

         IF(MOD(L,LPR).EQ.0)THEN
            CALL CSTAND(SYSOUT,L,BCF,HMX,HDS,PRO,DORE,PTCAGE)
         ENDIF
```

```
* DTP If SWPLOT is set, write out stand characteristics averaged for each
*     age-class as stored in PBIOM1, PBASA1, PLAI1, PDENS1 and PPROD1
         IF(SWPLOT.GT.0)THEN
            IF(SWDIST.GT.0)THEN
               IF((L*TIM.GT.600).AND.(L*TIM.LE.1100).AND.
     >            (MOD(L*TIM,100).EQ.0))THEN
                     CALL BYAGE (NAM,PTCAGE,TAX,DORE)
               ENDIF
            ELSE ! SWDIST=0 => no disturbances
               IF((L*TIM.LE.1100).AND.(MOD(L*TIM,100).EQ.0))THEN
                   CALL BYAGE (NAM,PTCAGE,TAX,DORE)
               ENDIF
            ENDIF
         ENDIF

200   CONTINUE

* optionally writes out unformatted system state description
      IF(IOUT.NE.0)THEN
         CALL OUT(NPAT)
      ENDIF

* DTP Write out disturbance interval data stored in array DSINT
      OPEN(UNIT=11,FILE='DISTURBS.DAT',STATUS='UNKNOWN')
      DO J=1,MAXDSI
         WRITE(11,505)J,DSINT(J)
      ENDDO
      WRITE(11,506)
      WRITE(11,508)
      DO L=1,MAXDIS
            WRITE(11,507) (DHIST(J,L),J=1,100)
*          WRITE(11,508)
      ENDDO
      CLOSE (UNIT=11)
  505 FORMAT('Patch Age: ', I4, ' Total Disturbances: ', I6)
  506 FORMAT(/'Summary of disturbance events')
  507 FORMAT(100(I4,','))
  508 FORMAT(/)

      CLOSE (UNIT=14)
      CLOSE (UNIT=15)
      CLOSE (UNIT=16)
      CLOSE (UNIT=17)
      CLOSE (UNIT=18)
      CLOSE (UNIT=19)
      IF(SWPLOT.GT.0)THEN
         CLOSE (UNIT=21)
         CLOSE (UNIT=22)
         CLOSE (UNIT=23)
         CLOSE (UNIT=24)
         CLOSE (UNIT=25)
      ENDIF
```

```
      IF(SWDBHD.GT.0)THEN
         CLOSE (UNIT=26)
      ENDIF

* writes current values of seeds for random number generator,
* to provide seeds for subsequent runs
*DTP      OPEN(UNIT=8,FILE='RANDOM.SEED',STATUS='UNKNOWN')
*DTP      WRITE(8,'(I8)')IE,IM,IG
*DTP      CLOSE (UNIT=8)

* Compilers execute the PAUSE statement differently.
* VAX/VMS returns the DCL-level and expects the command "continue" to
* continue the execution. The Microsoft Fortran77 and Absoft MacFortran
* only needs a single return. Check your manuals for the appropriate
* action.

*DTP  PAUSE 'NORMAL TERMINATION, PRESS RETURN TO QUIT'
      WRITE(SYSOUT,2)
      STOP ' '

* format statements:

1     FORMAT(/'**** Patch   ',I4,' after',I7,' years')
2     FORMAT(/' ** FORSKA2 - Normal Termination **')

      END  ! FORSKA2V MAIN PROGRAM

**************************************************************************

      SUBROUTINE LGTMOD(SYSOUT,SYSIN)
      IMPLICIT NONE

* landscape version 1990
* reads model parameters from file PARAM.DAT

*DTP 21 October 1998.
*    Changed Model configuration to allow more trees per plot. This has to be
*    fixed in all COMMON blocks. Put COMMONs into compar.h include files so
*    that these can be modified conveniently.

      INCLUDE 'compar.h'    ! global model parameters
      INCLUDE 'comrun.h'    ! settings for this run
      INCLUDE 'comsite.h'   ! site and climate variables
      INCLUDE 'comtax.h'    ! species parameters
      INCLUDE 'comtree.h'   ! tree parameters
      INCLUDE 'comdead.h'   ! dead tree parameters

* Local variables

      INTEGER SYSOUT, SYSIN
      CHARACTER*80 TITLE
      CHARACTER*40 FILENM
```

```
* opens input and output files

      OPEN(UNIT=1,FILE='paramsBF1a.dat',STATUS='OLD',ERR=100)
      GOTO 200

100   WRITE(SYSOUT,1)
101   WRITE(SYSOUT,2)
      READ(SYSIN,'(A40)')FILENM
      IF(FILENM(1:5).EQ.'     ')
     +                  STOP ' STOPPED: FILE SPECIFIED NOT VALID'
      OPEN(UNIT=1,FILE=FILENM,STATUS='OLD',ERR=102)
      GOTO 200
102   WRITE(SYSOUT,3)
      GOTO 101

200   OPEN(UNIT=3,FILE='FORCLI.OUT',STATUS='UNKNOWN')

* opens output files for input to SAS

      OPEN(UNIT=14,FILE='BASALA.DAT',STATUS='UNKNOWN')
      OPEN(UNIT=15,FILE='BIOMAS.DAT',STATUS='UNKNOWN')
      OPEN(UNIT=16,FILE='PROD.DAT',STATUS='UNKNOWN')
* DTP-- 15 July 1993
* Added new file DENSTY.DAT to keep track of mean stem densities
      OPEN(UNIT=17,FILE='DENSTY.DAT',STATUS='UNKNOWN')
* DTP-- 1994??: 'FOREST.DAT' provides a complete summary of forest-
* level output for input to a spreadsheet.
      OPEN(UNIT=18,FILE='FOREST.DAT',STATUS='UNKNOWN')
* DTP-- 15 August 1996: 'DEDTREES.DAT' provides a similar summary
* of forest level output of dead trees (omitting productivity) for
* input to a spreadsheet.
      OPEN(UNIT=19,FILE='DEDTREES.DAT',STATUS='UNKNOWN')

* reads and writes title and subtitle of the run

      READ(1,4,ERR=999,END=999)TITLE
      WRITE(SYSOUT,'(1X,A79)')TITLE(1:79)
      WRITE(3,'(/1X,A80)')TITLE

      READ(1,4,ERR=999,END=999)TITLE
      WRITE(SYSOUT,6)TITLE(1:79)
      WRITE(3,5)TITLE


************************************************************
**
** DTP 92/11/27  I decided to move the "soil water bucket"
**               over to the climate file.....
**               since it makes more sense to vary the
**               soil characteristics with the locations
```

```
**               at which the climate observations are made...
** However, for simplicity, since GT_ENV is called after the
** species parameters are read in, I will leave the code
** intact here, even though FCP will normally be overwritten
** by the value read in following LAT and CCP.
** N.B. Colin Prentice pointed out that FCP is not really
** the "field capacity" but (FCP - WP) = max available soil
**               water storage

** DTP 93/05/07  Experiment with modified values for
**     Timret and Gamma - The disturbance return interval and
**     conditional probability factor

* reads and writes site parameters:

* WMX:   max biomass (Mg/ha),
* WATC:  size of bucket (field capacity)

      READ(1,*,ERR=999,END=999)WMX,WATC
      WRITE(SYSOUT,7)WMX,WATC
      WRITE(3,7)WMX,WATC

* reads and writes MODEL run parameters:

* KCO:  light extinction coefficient,
* PAT:  patch size (ha),
* NPAT: number of patches,
* TIM:  timestep (yr),
* NTIM: number of timesteps,
* VINC: vertical integration step (m),
* DBH0: minimum diameter (cm),
* RHO:  steepness parameter for the mortality function
* TREF: reference temperature
* FCO2: internal/external CO2
* TIMRET: mean recurrence interval for disturbance
* GAMMA:  disturbance rate


      READ(1,*,ERR=999,END=999)KCO,PAT,NPAT,TIM,NTIM,VINC,DBH0,RHO,TREF,
     %                          FCO2,TIMRET,GAMMA
      WRITE(SYSOUT,9)KCO,PAT,NPAT
      WRITE(3,9)KCO,PAT,NPAT

      WRITE(SYSOUT,10)TIM,NTIM,TREF
      WRITE(3,10)TIM,NTIM,TREF

      IF(RHO.LE.20)THEN
         WRITE(SYSOUT,11)VINC,RHO
         WRITE(3,11)VINC,RHO

      ELSE
         WRITE(SYSOUT,12)VINC,RHO
```

```
         WRITE(3,12)VINC,RHO

      ENDIF
      WRITE(SYSOUT,13)DBH0
      WRITE(3,13)DBH0

      WRITE(SYSOUT,14)FCO2
      WRITE(3,14)FCO2

      WRITE(SYSOUT,15)TIMRET,GAMMA
      WRITE(3,15)TIMRET,GAMMA


*DTP  PAUSE 'PRESS RETURN TO CONTINUE'
      RETURN

999   WRITE(SYSOUT,20)
      WRITE(3,20)
*DTP  PAUSE 'PRESS RETURN TO QUIT'
      STOP 'FORSKA TERMINATED BECAUSE OF READ ERROR(S).'

* format statements

1     FORMAT(/' ERROR...... File PARAM.DAT not found!')
2     FORMAT(/' Type new FILENAME: ',$)
3     FORMAT(/' FILE NOT FOUND. RE-ENTER......')
4     FORMAT(A80)
5     FORMAT(1X,A80//1X,130('-'))
6     FORMAT(/1X,A79//1X,A79/1X,79('-'))
7     FORMAT(/' SITE PARAMETERS'//2X,'max stemwood biomass',24X,F6.1,
     %       7X,'Mg/ha'/2X,'bucket size (field capacity)',16X,F6.1,
     %       7X,'mm')
9     FORMAT(/' MODEL PARAMETERS'//2X,'light extinction coefficient',
     %       15X,F8.2/2X,'patch size',36X,F6.3,
     +'     ha'/2X,'number of patches',27X,I4)
10    FORMAT(2X,'timestep',36X,I4,9X,'yr'/
     +       2X,'number of timesteps',25X,I4,/
     %       2X,'reference temperature',23X,F6.1,'   oC')
11    FORMAT(2X,'vertical integration step',21X,F5.2,6X,'m'/2X
     +,'steepness parameter',25X,F6.1,7X,'(Continuous function)')
12    FORMAT(2X,'vertical integration step',21X,F5.2,6X,'m'/
     +2X,'steepness parameter',25X,F6.1,7X,'(step function)')
13    FORMAT(2X,'minimum starting diameter',20X,F7.2,5X,'cm')
14    FORMAT(2X,'internal/external CO2',24X,F7.2)
15    FORMAT(2X,'disturbance mean recurrence interval',9X,I4,/
     %       2X,'disturbance rate',29X,I4/)
20    FORMAT(/' ERROR IN READING MODEL PARAMETERS')

      END ! SUBROUTINE LGTMOD

************************************************************************
```

```
      SUBROUTINE LTVXT(SYSOUT,J,L,PTCAGE,DSINT,DHIST,DISNUM)
      IMPLICIT NONE

* CLIMATE and LANDSCAPE version 1990

*DTP 21 October 1998.
*    Changed Model configuration to allow more trees per plot. This has to be
*    fixed in all COMMON blocks. Put COMMONs into compar.h include files so
*    that these can be modified conveniently.

      INCLUDE 'compar.h'     ! global model parameters
      INCLUDE 'comrun.h'     ! settings for this run
      INCLUDE 'comsite.h'    ! site and climate variables
      INCLUDE 'comtax.h'     ! species parameters
      INCLUDE 'comtree.h'    ! tree parameters
*      INCLUDE 'comdead.h'    ! dead tree parameters

* subroutine arguments
      INTEGER SYSOUT, J, L,PTCAGE(MAXPAT),
     >        DSINT(MAXDSI),DHIST(MAXPAT,MAXDIS),DISNUM(MAXPAT)

* function declarations

      REAL    HEIGHT,DBHINC,PDEATH
      INTEGER MORT,WIPEUT

* local variables

      REAL    HTOP,TOTBIO,BIO,GSLITE,M4LITE
C     REAL    LIGHT

      PARAMETER(HTOP=55.)
      INTEGER NTREES,I,K,M

      REAL    Z,LAI,TLA,SLA,PD,PROBDS,RGAMMA,RAGE,RTIMRT,RTIM
      REAL    A(MAXIND),D(MAXIND),DINC(MAXIND),FA(MAXIND),
     +        FD(MAXIND),G(MAXIND),H(MAXIND),
     +        H1(MAXIND),H2(MAXIND),P(MAXSPE),
     +        DDH(MAXSPE),CO2ALP(MAXSPE)

*TLS moved AMDGSC(MAXSPE) to include file comtax.h.

* assigns each tree its diameter (D), height (H), bole height (H1),
* and leaf area per unit height (FD). Counts number of trees
* (NTREES), and sums (diameter**2)*height for the patch (DDH).
* Initializes each tree's potential assimilation (A) and D2H increment (G)


      NTREES=0
      TOTBIO=0

* DTP replaced next line with the one following.
```

```
*      DO 99 M=1,MAXSPE
       DO 99 M=1,NTAX        ! we only need to go through ntax spp.
         DDH(M)=0.0
99     CONTINUE

* if first year set patch age to 1

C        IF(L.EQ.1)PTCAGE(J)=1  !TLS already assigned in cetbl

       DO 100 K=1,MAXIND
          IF(TAX(J,K).EQ.0) GOTO 101
          D(K)=DBH(J,K)
          IF(TAX(J,K).GT.0)THEN
            H(K)=HEIGHT(D(K),HMX(TAX(J,K)),HDS(TAX(J,K)))
            IF(H(K).GT.HTOP)THEN  ! Debug code added by DTP 92/04/30.
D             write (sysout,1001) J,K,L,H(K),HTOP,D(K),TAX(J,K),
D     +                           HDS(TAX(J,K))
1001          FORMAT (' J=',I5, ' K=',I5,' L=',I5,' H(K)=',E10.3E2,
      +               'HTOP=',F8.3,' D(K)=',F8.3,' TAX(J,K)=',I5,
      +               'HDS(TAX(J,K))=',F8.3)
              STOP 'tree too high'
            ENDIF
            H1(K)=HBC(J,K)
            FA(K)=LEA(J,K)
            FD(K)=FA(K)/(H(K)-H1(K))
            A(K)=0.0
            G(K)=0.0
            DDH(TAX(J,K))=DDH(TAX(J,K))+D(K)*D(K)*H(K)
            NTREES=K
          ENDIF
100       CONTINUE
101    CONTINUE


* computes current biomass (BIO) species DDH total and species BCF

* DTP Replaced next line with one following
*      DO 102 K=1,MAXSPE
       DO 102 K=1,NTAX
         TOTBIO=TOTBIO+(DDH(K)*BCF(K))
102    CONTINUE

       BIO=TOTBIO/1.E3/PAT

* integrates total leaf area and tree-by-tree potential assimilation
* in vertical steps of size VINC

       TLA=0.0
       DO 200 Z=HTOP,VINC,-VINC

          LAI=TLA/PAT/1.E4
          GSLITE=EXP(-KCO*LAI)*XGSINS
```

```
          M4LITE=EXP(-KCO*LAI)*XM4INS

       DO 201 I=1,NTAX

* Apply CO2mx to half-saturation point (ALP)

            CO2ALP(I)=ALP(I)*CO2MX(I)

* deciduous or evergreen
             IF(DORE(I).EQ.0)THEN

                P(I)=(KCO*GSLITE-LCP(I))/(KCO*GSLITE+CO2ALP(I)-LCP(I))

             ELSE

                P(I)=(KCO*M4LITE-LCP(I))/(KCO*M4LITE+CO2ALP(I)-LCP(I))
             ENDIF

201         CONTINUE

       DO 202 K=1,NTREES
       IF(H(K).LT.Z.OR.H1(K).GE.Z)GOTO 202

* amend the GSC for climate according to climate/growth multipliers
* TLS AMDGSC(MAXSPE) moved to comtax.h. Assigned first in cetbl and
* not needed again here. If used here needs to be moved outside of NTREE loop
* or becomes undefined for species without individuals on the patch and
* affects maximum diameter increment (INC(J,K)) calculation that follows.

C       AMDGSC(TAX(J,K))=GSC(TAX(J,K))*GDDMX(TAX(J,K))
C   +                        *DRMX(TAX(J,K))*TCMX(TAX(J,K))
C    %                        *TFTMX(TAX(J,K),L)*CO2MX(TAX(J,K))

* TLS- changed to abbreviated write out to test
* WRITE(sysout,10)J,K,AMDGSC(TAX(J,K)),GSC(TAX(J,K)),GDDMX(TAX(J,K))
c       WRITE(30,10)J,K,AMDGSC(TAX(J,K))
*    +           ,DRMX(TAX(J,K)),TCMX(TAX(J,K))
10      FORMAT(1X,I4,2X,I4,2X,F6.3)


* DTP: The following statement could be replaced by the next one. This
* follows Lasch and Lindner (1995) at Changhui's suggestion. However,
* a test run shows that for BFTCS area at least, it does not have much
* effect on biomass, and in fact reduces it on average, rather than
* increasing it as Marcus reported.
*            A(K)=A(K)+AMDGSC(TAX(J,K))*P(TAX(J,K))*FD(K)*
*    +           (1.-BIO/WMX)*VINC*TIM
             A(K)=A(K)+AMDGSC(TAX(J,K))*P(TAX(J,K))*FD(K)*
     +           (1.-exp(-0.01*(WMX-BIO)))*VINC*TIM
             TLA=TLA+FD(K)*VINC
202          CONTINUE
200        CONTINUE
```

```
* computes each tree's diameter increment (corrected for sapwood
* maintenance cost), new diameter, and a new value for leaf area
* per unit height.

      DO 300 K=1,NTREES

         G(K)=DIM(A(K),SAPRES(TAX(J,K),L)*FA(K)*0.5*(H(K)+H1(K))*TIM)
         TGE(K)=G(K)/FA(K)/GOP(TAX(J,K))
         DINC(K)=DBHINC(G(K),D(K),HMX(TAX(J,K)),HDS(TAX(J,K)))
         FA(K)=MAX(FA(K)+2*LAC(TAX(J,K))*D(K)*DINC(K)-LAF(TAX(J,K))
     +        *FA(K)*TIM, 0.0)
         D(K)=D(K)+DINC(K)
         H(K)=HEIGHT(D(K),HMX(TAX(J,K)),HDS(TAX(J,K)))
         FD(K)=FA(K)/(H(K)-H1(K))
         H2(K)=H1(K)
300     CONTINUE

* removes any leaves that would be below compensation point, and raises
* bole heights (H2) accordingly

      TLA=0.0
      DO 400 Z=HTOP,VINC,-VINC
         LAI=TLA/PAT/1.E4

         GSLITE=EXP(-KCO*LAI)*XGSINS
         M4LITE=EXP(-KCO*LAI)*XM4INS

         DO 401 K=1,NTREES
           IF(H(K).LT.Z.OR.H1(K).GE.Z)GOTO 401
           TLA=TLA+FD(K)*VINC
* deciduous or evergreen
           IF(DORE(TAX(J,K)).EQ.0)THEN
             IF(KCO*GSLITE.LT.LCP(TAX(J,K)))H2(K)=MAX(Z,H2(K))
           ELSE
             IF(KCO*M4LITE.LT.LCP(TAX(J,K)))H2(K)=MAX(Z,H2(K))
           ENDIF

  401    CONTINUE
  400 CONTINUE

* computes the maximal diameter increments under the new canopy
* conditions, for use in subroutine ETBL

      DO 500 I=1,NTAX

* deciduous or evergreen
         IF(DORE(I).EQ.0)THEN
            IF(KCO*GSLITE.LT.LCP(I))THEN
              INC(J,I)=0.0
            ELSE
              P(I)=(KCO*GSLITE-LCP(I))/(KCO*GSLITE+CO2ALP(I)-LCP(I))
```

```
*DTP replace following statement by that from Lasch and Lindner(1995)
*             SLA=LAC(I)*(DBH0**2)*(1-BIO/WMX)*TIM*P(I)*AMDGSC(I)
              SLA=LAC(I)*(DBH0**2)*(1-exp(-0.01*(WMX-BIO)))
     +            *TIM*P(I)*AMDGSC(I)
              INC(J,I)=MAX(0.0,DBHINC(SLA,DBH0,HMX(I),HDS(I)))
            ENDIF
         ELSE
            IF(KCO*M4LITE.LT.LCP(I))THEN
              INC(J,I)=0.0
            ELSE
              P(I)=(KCO*M4LITE-LCP(I))/(KCO*M4LITE+CO2ALP(I)-LCP(I))
*DTP replace following statement by that from Lasch and Lindner(1995)
*             SLA=LAC(I)*(DBH0**2)*(1-BIO/WMX)*TIM*P(I)*AMDGSC(I)
              SLA=LAC(I)*(DBH0**2)*(1-exp(-0.01*(WMX-BIO)))
     +            *TIM*P(I)*AMDGSC(I)
              INC(J,I)=MAX(0.0,DBHINC(SLA,DBH0,HMX(I),HDS(I)))
            ENDIF
         ENDIF

  500 CONTINUE

* assigns new values of state variables. Randomly selects trees to be
* killed (flagged with negative TAX values) with probabilities computed
* from their diameter increments during the current timestep
      DO 600 K=1,NTREES
         DBH(J,K)=D(K)
         HBC(J,K)=H2(K)
         LEA(J,K)=FD(K)*(H(K)-H2(K))
         AGE(J,K)=AGE(J,K)+TIM
         PD=PDEATH(TGE(K),UMN(TAX(J,K)),UMX(TAX(J,K)),TDI(TAX(J,K)),
     +      RHO,TIM)
         TAX(J,K)=MORT(PD)*TAX(J,K)
600      CONTINUE


*DTP - 28/07/95 Following Code checks value of SWDIST, the disturbance
*               switch. If Set to 0, then disturbances are suppressed.

         IF(SWDIST.EQ.1)THEN

* set up disturbance function - get probability worked out depending
* on time since last disturbance.

* make variables real must be an easier way

          RAGE=PTCAGE(J)
          RTIM= TIM
          RTIMRT=TIMRET
          RGAMMA=GAMMA

            PROBDS=1-(EXP(-((((RAGE+RTIM)/RTIMRT)**RGAMMA)-
     %             ((RAGE/RTIMRT)**RGAMMA))))
```

```
* TLS PTCAGE update here deleted. Age should be updated FOLLOWING
* disturbance. Not prior to AND following disturbance as was case.

c         PTCAGE(J)=PTCAGE(J)+TIM  !tls this is repeated below
c        WRITE(SYSOUT,456)PROBDS

* do not print out to save much paper

C         WRITE(3,456)PROBDS
456     FORMAT(1X,'Probability of disturbance: ',F8.5)

* check to see if a patch has been wiped out in this period and
* if so set TAX to negative for every tree in the patch

           IF(WIPEUT(PROBDS).LT.0)THEN
             PTCAGE(J)=MIN(PTCAGE(J),MAXDSI)      ! Ensure we don't overrun array
bounds
             DSINT(PTCAGE(J))=DSINT(PTCAGE(J))+1
              IF(DISNUM(J).LT.MAXDIS)THEN
               DISNUM(J)=DISNUM(J)+1
               DHIST(J,DISNUM(J))=L*TIM           ! This is wrong when L is
randomised
              ENDIF
*DTP--            WRITE(SYSOUT,1)J,L*TIM
             WRITE(3,1)J,L*TIM

* if patch disturbed reset age to 1

             PTCAGE(J)=1

* set TAX to negative now

             DO 700 K=1,NTREES
! Changed TAX(J,K)=-TAX(J,K) to =-ABS(TAX(J,K))
               TAX(J,K)=-ABS(TAX(J,K))
!              TAX(J,K)=-TAX(J,K)
700          CONTINUE

          ELSE
           PTCAGE(J)=PTCAGE(J)+TIM  ! This must be done if no disturbances
(PROBDS.GT.0)
          ENDIF       ! IF(WIPEUT(PROBDS).LT.0)

       ELSE
           PTCAGE(J)=PTCAGE(J)+TIM  !update patch age if SWDIST.LE.0
       ENDIF ! IF(SWDIST.EQ.1)
      RETURN


* FORMAT
1     FORMAT(/'***Patch  ',I4,' wiped out after',I7,' years - patch
```

```
     + reinitialised***')
2     FORMAT(x,f7.8,10x,f7.8)
      END  ! SUBROUTINE LTVXT

******************************************************************************

      subroutine getpro(sysout)

      implicit none

* Loads pre-processed environmental data generated by ENVIRO, and bypassing
* all the computation needed in FORSKA. Uses data file "enviro.inp" instead
* of "climate.inp"

*DTP 21 October 1998.
*    Changed Model configuration to allow more trees per plot. This has to be
*    fixed in all COMMON blocks. Put COMMONs into compar.h include files so
*    that these can be modified conveniently.

      INCLUDE 'compar.h'     ! global model parameters
      INCLUDE 'comrun.h'     ! settings for this run
      INCLUDE 'comsite.h'    ! site and climate variables
      INCLUDE 'comtax.h'     ! species parameters
      INCLUDE 'comtree.h'    ! tree parameters
      INCLUDE 'comdead.h'    ! dead tree parameters

* subroutine argument
      INTEGER SYSOUT

* local variables

      integer k,l,lnblnk,index
      character*20 stname,timstr
      character*24 fdate,datstr

* TLS  read in daily variable climate data from envirod.inp
C     open(10,file='enviro.inp',status='old',shared,readonly)
      open(10,file='envirod.inp',status='old')


* DTP 92/12/09 - I added the following statements so that output from individual
* runs would be stamped with the file type, date, time and climate station name.
* Read in climate station name, and echo to output files, together with type,
date,
* time and station name stamp....
* NOTE: FUNCTIONs lnblnk() and fdate() are specific to Sun F77

      read(10,110,err=999,end=999) stname
      l=index(stname,' e')    ! look for start of "environmental" in STNAME
      if(l.gt.0) stname=stname(1:l-1)  ! truncate to end of station name
      l=lnblnk(stname)                 ! get length of truncated STNAME
```

```
      datstr=fdate()
      timstr=datstr(12:19)
      datstr=datstr(9:11)//datstr(5:8)//datstr(21:24)

      write(3,99)  timstr,datstr,stname
      write(14,99) timstr,datstr,stname
      write(15,99) timstr,datstr,stname
      write(16,99) timstr,datstr,stname
      write(17,99) timstr,datstr,stname
***********************************************************************
* DTP 99/06/24: Changed these for Pingree Park Experiment
*      write(18,99) timstr,datstr,stname
      write(19,99) timstr,datstr,stname
      write(20,99) timstr,datstr,stname

      write(14,98) 'BASALA'
      write(15,98) 'BIOMAS'
      write(16,98) 'PROD  '
      write(17,98) 'DENSTY'
***********************************************************************
* DTP 99/06/24: Changed these for Pingree Park Experiment
*      write(18,97) 'YEAR SPP. B.A. BIOMASS PROD. DENSITY AV.TREE'

      write(18, 506)
 506  FORMAT ('\tTime\tABBA_B\tBEPA_B\tLALA_B\tPIGL_B\tPIMA_B\tPIBA_B\t'
     >        'PIST_B\tPOBA_B\tPOTR_B\tTHOC_B\tOTHR_B\t'
     >        'ABBA_#\tBEPA_#\tLALA_#\tPIGL_#\tPIMA_#\tPIBA_#\t'
     >        'PIST_#\tPOBA_#\tPOTR_#\tTHOC_#\tOTHR_#\tLAI')

      write(19,97) 'YEAR SPP. B.A. BIOMASS DENSITY AV.TREE'

   99 FORMAT(' This simulation started at ',A8,' on ',A11,
     >       ' using climate data for ',A12)
   98 FORMAT(A6)
   97 FORMAT(A36)
  110 FORMAT(A20///)    ! Skip past end of current and next two lines

* write environmental headings to forcli.out and screen

      write(sysout,100)
      write(3,100)
      write(sysout,101)
      write(3,101)

* set up loop to read environmental data for each year to ntim*tim

      do l=1,(ntim*tim)

* read environment data for timestep/year l from ENVIRO.INP

      read(10,*,err=999,end=999) yr(l),gdd(l),gsdri(l),m4dri(l),
     >              gsins(l),m4ins(l),tcold(l),twarm(l),addccp(l)
```

```
* echo the new data back to the screen (at least for now)
      write(sysout,102)yr(l),gdd(l),gsdri(l),m4dri(l),
     >              gsins(l),m4ins(l),tcold(l),twarm(l),addccp(l)
C      write(3,102)

* Similarly read in individual species multipliers (and echo to screen?)
        do k=1,ntax
          read(10,*,err=999,end=999) mutmx(k,l),sapres(k,l),
     >         tftmx(k,l)
*          write(sysout,103) mutmx(k,l),sapres(k,l),tftmx(k,l)
C          write(3,103) mutmx(k,l),sapres(k,l),tftmx(k,l)
        enddo

      enddo ! l=1,(ntim*tim)

*DTP  pause 'press return to continue'
      return


  999 write(sysout,200)
      write(3,200)
*DTP  pause 'Press return to quit'
      stop 'Forska terminated because of read errors.'

* format statements
  100 format(1x,/'Site environmental data input to model'//)
  101 format(1x,'year',3x,'gdd',4x,'gsdri',2x,'-4dri',2x,
     %       'gsins',2x,'m4ins',2x,'tcold',2x,'twarm',2x,'addCO2'/)
  102 format(1x,i4,1x,f6.0,2x,f6.3,1x,f6.3,1x,f6.1,1x,f6.1,1x,f6.1,
     %       1x,f6.1,1x,f6.1)
  103 format(1x,f7.4,1x,f7.4,1x,f7.4)
  200 format(/' Error in reading environmental data')

      end  ! SUBROUTINE GETPRO

*----------------------------------------------------------------------------*

      SUBROUTINE CGTSPE(SYSOUT,NTAX)
      IMPLICIT NONE
* CLIMATE and LANDSCAPE version 89.10.23

* reads species parameters

*DTP 21 October 1998.
*    Changed Model configuration to allow more trees per plot. This has to be
*    fixed in all COMMON blocks. Put COMMONs into compar.h include files so
*    that these can be modified conveniently.

      INCLUDE 'compar.h'    ! global model parameters
      INCLUDE 'comtax.h'    ! species parameters
      INCLUDE 'comnames.h'  ! species names
```

```
* local variables

C     REAL    CHECK
      INTEGER SYSOUT,NTAX,I,J,K

* reads number of taxa (NTAX)

      READ(1,*,ERR=999,END=999)NTAX

* reads for each taxon:

*   NAM(I): name (8 characters)
*   HMX(I): max height (m)
*   HDS(I): initial slope of diameter vs height (m/cm)
*   ALP(I): half-saturation point (umol/m**2/s)
*   LCP(I): compensation point (umol/m**2/s)
*   GSC(I): growth constant (cm**2/m/yr)
*   EST(I): sapling establishment rate (/ha/yr)
*   TDI(I): threshold relative growth efficiency for increased mortality
*   UMN(I): intrinsic mortality rate (/yr)
*   UMX(I): suppressed mortality rate (/yr)
*   SPR(I): number of sprouts per tree (0.0 or greater)
*   SMN(I): minimum diameter for sprouting (cm)
*   LAC(I): initial leaf area/D2 ratio (m**2/cm**2)
*   LAF(I): sapwood turnover rate (/yr)
*   BCF(I): stemwood biomass conversion factor (kg/cm**2/m)
*     R(I): volumetric sapwood maintenance cost (/yr)
*   Q10(I): rate of increase of respiration
*  TMIN(I): minimum temperature for assimilation
*  TMAX(I): maximum temperature for assimilation
*   CCP(I): species compensation point
*   DRI(I): maximum tolerated drought-index
*MINGDD(I): minimum growing degree-days
* MINTC(I): minimum temperature of coldest month (degrees C)
* MAXTC(I): maximum temperature of coldest month (degrees C)
* MINTW(I): minimum temperature of warmest month (degrees C)
*  DORE(I): deciduous or evergreen 0=deciduous,1=evergreen

      DO 100 I=1,NTAX
*         READ(1,1,ERR=999,END=999) NAM(I)
         READ(1,*,ERR=999,END=999) NAM(I),HMX(I),HDS(I),ALP(I),LCP(I),
     +                             GSC(I),EST(I),TDI(I),UMN(I),UMX(I),
     +                             SPR(I),SMN(I),LAC(I),LAF(I),BCF(I),
     +                             R(I),Q10(I),TMIN(I),TMAX(I),CCP(I),
     +                             DRI(I),MINGDD(I),MINTC(I),
     +                             MAXTC(I),MINTW(I),DORE(I)

***********************************************************************
* DTP 9 October 1995. Temporary fix to play with drought sensitivity for
* use in "monthly climate mode".
```

```
*     DRI(I)=DRI(I)*1.25  ! Increase all drought resistance by 25%

* DTP 4 Jan 1996. Getting desperate here. Let's try this....
C     DRI(I)=(DRI(I)+0.165)*0.75  ! Increase drought resistances on
                                  ! sliding scale (greatest increase at
                                  ! low end)

************************************************************************

*        DRI(I)=DRI(I) * 0.72      ! Reduce drought resistance by 20%

         IF(SPR(I).EQ.0)SMN(I)=0.0

         IF(MINTC(I).GT.MAXTC(I))THEN
            WRITE (SYSOUT,30)I
            WRITE (3,30)I
            STOP'FORSKA TERMINATED - minimum tc exceeds maximum tc.'
         ENDIF
100      CONTINUE

* writes species parameters to output file on FORCLI.OUT

      DO 200 J=1,NTAX,4
         K=J+3
         IF(K.GT.NTAX)K=NTAX

         WRITE(3,*)
         WRITE(3,2)  (NAM(I),I=J,K)
         WRITE(3,3)  (HMX(I),I=J,K)
         WRITE(3,4)  (HDS(I),I=J,K)
         WRITE(3,5)  (LAC(I),I=J,K)
         WRITE(3,6)  (GSC(I),I=J,K)
         WRITE(3,7)  (LAF(I),I=J,K)
         WRITE(3,8)  (R(I),I=J,K)
         WRITE(3,9)  (Q10(I),I=J,K)
         WRITE(3,10) (BCF(I),I=J,K)
         WRITE(3,11) (EST(I),I=J,K)
         WRITE(3,12) (SPR(I),I=J,K)
         WRITE(3,13) (SMN(I),I=J,K)
         WRITE(3,15) (ALP(I),I=J,K)
         WRITE(3,16) (LCP(I),I=J,K)
         WRITE(3,17) (TDI(I),I=J,K)
         WRITE(3,18) (UMN(I),I=J,K)
         WRITE(3,19) (UMX(I),I=J,K)
         WRITE(3,20) (TMIN(I),I=J,K)
         WRITE(3,21) (TMAX(I),I=J,K)
         WRITE(3,22) (CCP(I),I=J,K)
         WRITE(3,23) (DRI(I),I=J,K)
         WRITE(3,24) (MINGDD(I),I=J,K)
         WRITE(3,25)  (MINTC(I),I=J,K)
         WRITE(3,26)  (MAXTC(I),I=J,K)
         WRITE(3,27)  (MINTW(I),I=J,K)
```

```
         WRITE(3,28)   (DORE(I),I=J,K)
200      CONTINUE

* write species parameters to the screen

c      DO 300 I=1,NTAX
c         WRITE(SYSOUT,2)  NAM(I)
c         WRITE(SYSOUT,3)  HMX(I)
c         WRITE(SYSOUT,4)  HDS(I)
c         WRITE(SYSOUT,5)  LAC(I)
c         WRITE(SYSOUT,6)  GSC(I)
c         WRITE(SYSOUT,7)  LAF(I)
c         WRITE(SYSOUT,8)  R(I)
C         WRITE(SYSOUT,9)  Q10(I)
C         WRITE(SYSOUT,10) BCF(I)
c         WRITE(SYSOUT,11)  EST(I)
c         WRITE(SYSOUT,12) SPR(I)
c         WRITE(SYSOUT,13) SMN(I)
c         WRITE(SYSOUT,15) ALP(I)
c         WRITE(SYSOUT,16) LCP(I)
c         WRITE(SYSOUT,17) TDI(I)
c         WRITE(SYSOUT,18) UMN(I)
c         WRITE(SYSOUT,19) UMX(I)
C         WRITE(SYSOUT,20) TMIN(I)
C         WRITE(SYSOUT,21) TMAX(I)
C         WRITE(SYSOUT,22) CCP(I)
c         WRITE(SYSOUT,23) DRI(I)
c         WRITE(SYSOUT,24) MINGDD(I)
c         WRITE(SYSOUT,25) MINTC(I)
c         WRITE(SYSOUT,26) MAXTC(I)
c         WRITE(SYSOUT,27) MINTW(I)
c         WRITE(SYSOUT,28)  DORE(I)

c         WRITE(SYSOUT,'(1X)')
c         PAUSE 'PRESS RETURN TO CONTINUE'
c300      CONTINUE
      RETURN

* error messages

999   WRITE(SYSOUT,30)I
      WRITE(3,30)I
*DTP  PAUSE 'PRESS RETURN TO QUIT'
      STOP 'FORSKA TERMINATED BECAUSE OF READ ERROR(S).'

* format statements

1     FORMAT(A8)
2     FORMAT(/1X,'SPECIES NAME:    ..............................'
     +,'.............       ',4(A8,7X))
3     FORMAT(/1X,'maximum height (m)     ...........................'
     +,'..........',4(F10.1,3X))
```

```
4      FORMAT(1X,'initial slope of diameter vs height (m/cm)    '
     +,'..............',4(F11.2,2X))
5      FORMAT(/1X,'initial ratio of leaf area to diameter**2 ',
     +            '  (m**2/cm**2) ...   ',4(F10.3,3X))
6      FORMAT(1X,'growth constant (cm**2/m/yr)   ..................'
     +,'..........',4(F10.1,3X))
7      FORMAT(/1X,'sapwood turnover rate (/yr)  ....................'
     +,'.........',4F13.4)
8      FORMAT(1X,'volumetric sapwood m/cost (cm**2 /m**2 /yr) .......'
     +,'........',4F13.4)
9      FORMAT(1X,'rate of increase of respiration (yr)...............'
     %,'........',4F13.4)
10     FORMAT(1X,'stemwod biomass conversion factor (kg/cm**2/m).....'
     %,'........',4F13.4)
11     FORMAT(/1X,'sapling establishment rate (/ha/yr) ...............'
     +,'........',4(F10.1,3X))
12     FORMAT(1X,'number of sprouts per tree (0 or greater) ........'
     +,'.........',4(F10.2,3X))
13     FORMAT(1X,'minimum diameter for sprouting  (cm) .............'
     +,'......... ',4(F10.2,3X))
15     FORMAT(/1X,'half-saturation point (umol/m**2/s)  '
     +,'......................',4(F10.1,3X))
16     FORMAT(1X,'compensation point (umol/m**2/s)    ..............'
     +,'..........',4(F10.1,3X))
17     FORMAT(/1X,'threshhold relative growth effiency for increased'
     +,' mortality ',4(F11.3,2X))
18     FORMAT(1X,'intrinsic mortality rate (/yr) ....................'
     +,'........',4F13.4)
19     FORMAT(1X,'suppressed mortality rate (/yr) ...................'
     +,'........',4(F11.2,2X))
20     FORMAT(1X,'minimum temperature for respiration (deg. C).......'
     %,'........',4(F10.1,3X))
21     FORMAT(1X,'maximum temperature for respiration (deg. C).......'
     %,'........',4(F10.1,3X))
22     FORMAT(1X,'CO2 compensation point (ppm).......................'
     %,'........',4(F11.2,2X))
23     FORMAT(/1X,'maximum tolerated drought-index ...................'
     +,'........',4(F11.2,2X))
24     FORMAT(1X,'minimum growing degree-days (base 5 deg. C)........'
     +,'........',4(F10.1,3X))
25     FORMAT(1X,'minimum temperature of coldest month (deg. C)......'
     +,'........',4(F10.1,3x))
26     FORMAT(1X,'maximum temperature of coldest month (deg. C)......'
     +,'........',4(F10.1,3x))
27     FORMAT(1X,'maximum temperature of warmest month (deg. C)......'
     %,'........',4(F10.1,3x))
28     FORMAT(1X,'deciduous (0) or evergreen (1).....................'
     %,'........',4(9X,I1,3x))

30     FORMAT(/' ERROR IN READING INPUT DATA FOR SPECIES',I4)

       END  ! SUBROUTINE CGTSPE
```

```
******************************************************************************

      SUBROUTINE CGTOUT(SYSOUT,NTIM,TIM,INIT,IOUT,NTAX)
      IMPLICIT NONE

* CLIMATE and LANDSCAPE version 89.10.24

* reads initialization option (INIT: nonzero for read in), termination option
* (nonzero for write out), how often to print stand description (timesteps)

*DTP 21 October 1998.
*    Changed Model configuration to allow more trees per plot. This has to be
*    fixed in all COMMON blocks. Put COMMONs into compar.h include files so
*    that these can be modified conveniently.

      INCLUDE 'compar.h'     ! global model parameters
      INCLUDE 'comnames.h'    ! species names

* subroutine arguments
      INTEGER SYSOUT,NTIM,TIM,INIT,IOUT,NTAX

* local variables
      INTEGER J

      READ(1,*,ERR=910,END=910)INIT
      IF(INIT.NE.0)THEN
         INIT=1
         WRITE(SYSOUT,1)
         WRITE(3,1)
      ENDIF
      GOTO100
910   WRITE(SYSOUT,4)'1'
      WRITE(3,4)'1'
      INIT=0

100   READ(1,*,ERR=920,END=920)IOUT
      IF(IOUT.NE.0)THEN
         IOUT=1
         WRITE(SYSOUT,2)
         WRITE(3,2)
      ENDIF
      GOTO200
920   WRITE(SYSOUT,4)'2'
      WRITE(3,4)'2'
      IOUT=0

200   READ(1,*,ERR=930,END=930)LPR
      IF(TIM*LPR.GT.TIM*NTIM)LPR=INT(NTIM*TIM)
      GOTO300
930   WRITE(SYSOUT,4)'3'
      WRITE(3,4)'3'
```

```
      LPR=INT(NTIM*TIM)

300   READ(1,*,ERR=940,END=940)WPAT
      IF(WPAT.NE.0)WPAT=1
      GOTO400
940   WRITE(SYSOUT,4)'4'
      WRITE(3,4)'4'
      WPAT=0

400   READ(1,*,ERR=950,END=950)START
      IF(START.GT.TIM*NTIM)START=TIM*NTIM
      IF(START.GT.0.0)THEN
        WRITE(3,3)START
      ENDIF
      GOTO500
950   WRITE(SYSOUT,4)'5'
      WRITE(3,4)'5'
      START=0

500   READ(1,*,ERR=960,END=960)SWCO2
      GOTO600
960   WRITE(SYSOUT,4)'6'
      WRITE(3,4)'6'
      SWCO2=0

*DTP-- 28/07/95 Added following to switch disturbances on (default), or off

600   READ(1,*,ERR=970,END=970)SWDIST
      GOTO650
970   WRITE(SYSOUT,4)'7'
      WRITE(3,4)'7'
      SWDIST=1

*DTP-- 12/01/96 Added following to switch climate data input:
*      from climate.inp (default) off
*      from enviro.inp  (new!!! ) on

650   READ(1,*,ERR=980,END=980)SWCLIM
      GOTO660
980   WRITE(SYSOUT,4)'8'
      WRITE(3,4)'8'
      SWCLIM=0

* DTP-- 23/09/96 Added following to switch on single plot output every output
interval

 660  READ(1,*,ERR=990,END=990)SWPLOT
* DTP-- 24 September 1996: Following *.DAT files (UNITS 21-24)
* will contain summaries of stand-indicators for each plot (to
* a max of 100?)
      IF(SWPLOT.GT.0)THEN
         OPEN(UNIT=21,FILE='PLT_BIOM.DAT',STATUS='UNKNOWN')
```

```
          OPEN(UNIT=22,FILE='PLT_BASA.DAT',STATUS='UNKNOWN')
          OPEN(UNIT=23,FILE='PLT_LAI.DAT',STATUS='UNKNOWN')
          OPEN(UNIT=24,FILE='PLT_DENS.DAT',STATUS='UNKNOWN')
          OPEN(UNIT=25,FILE='PLT_PROD.DAT',STATUS='UNKNOWN')
          WRITE (21,5) (NAM(J),J=1,NTAX)
          WRITE (22,5) (NAM(J),J=1,NTAX)
          WRITE (23,5) (NAM(J),J=1,NTAX)
          WRITE (24,5) (NAM(J),J=1,NTAX)
          WRITE (25,5) (NAM(J),J=1,NTAX)
       ENDIF
       GOTO670
 990   WRITE(SYSOUT,4)'9'
       WRITE(3,4)'9'
       SWPLOT=0

 670   READ(1,*,ERR=995,END=995)SWDBHD
* DTP -- 20 Jan 1997: Print out DBH class distributions
       IF(SWDBHD.GT.0)THEN
          OPEN(UNIT=26,FILE='DBHCLS.DAT',STATUS='UNKNOWN')
       ENDIF
       GOTO700
 995   WRITE(SYSOUT,4)'10'
       WRITE(3,4)'10'
       SWDBHD=0

700    CLOSE(UNIT=1)
       RETURN

* format statements:

1      FORMAT(/1X,'Initial array is read from STAND.INI.')
2      FORMAT(/1X,'Final array will be written to NEWSTAND.INI.')
3      FORMAT(/1X,'The description of the simulated stand starts after',
     + I6,' years.')
4      FORMAT(/' ERROR IN READING IN- OR OUTPUT SPECIFIER ',A1)
*DTP 5     FORMAT('PLOT,AGE,',<NTAX>(A4,','),'HDWD,SFWD,TOTAL')
 5     FORMAT('PLOT,AGE,',20(A4,','),'HDWD,SFWD,TOTAL')


       END  ! SUBROUTINE CGTOUT

******************************************************************************

       SUBROUTINE CGTRAN()
       IMPLICIT NONE

*DTP 21 October 1998.
*    Changed Model configuration to allow more trees per plot. This has to be
*    fixed in all COMMON blocks. Put COMMONs into compar.h include files so
*    that these can be modified conveniently.

       INCLUDE 'compar.h'     ! global model parameters
```

```
* reads seeds for random number generator

      OPEN(UNIT=8,file='RANDOM.SEED',STATUS='OLD',ERR=999)
      READ(8,*,ERR=999,END=999)IE
      READ(8,*,ERR=999,END=999)IM
      READ(8,*,ERR=999,END=999)IG
      CLOSE (UNIT=8)
100   WRITE(3,1)IE,IM,IG
      RETURN
999   IE=2845
      IM=543
      IG=14267
      WRITE(3,2)
      GOTO 100

* format statements

1     FORMAT(/' The seeds for the RANDOM number generator are: ',3I7)
2     FORMAT(/' The file RANDOM.SEED is not found or not complete.'
     +          ,' Standegard seeds used!')

      END  ! SUBROUTINE CGTRAN

***********************************************************************

      INTEGER FUNCTION  WIPEUT(PROBDS)

* LANDSCAPE VERSION ONLY 89.10.29

      REAL RAND2,PROBDS

* Patches are flagged for complete destruction and re-initialisation
* with a probability of PROBDS worked out in LTVXT routine

      IF(RAND2().LT.PROBDS)THEN
         WIPEUT=-1
      ELSE
         WIPEUT=1
      ENDIF
      RETURN

      END  ! INTEGER FUNCTIONC WIPEUT

***********************************************************************

      SUBROUTINE OUT(NPAT)
      IMPLICIT NONE

* writes the final array

*DTP 21 October 1998.
```

```
*    Changed Model configuration to allow more trees per plot. This has to be
*    fixed in all COMMON blocks. Put COMMONs into compar.h include files so
*    that these can be modified conveniently.

      INCLUDE 'compar.h'     ! global model parameters
      INCLUDE 'comtree.h'    ! tree parameters

* subroutine argument
      INTEGER NPAT

* local variables
      INTEGER J,K

* TLS amended to correct writing of zeros to NEWSTAND.INI list of
* individuals.

      OPEN(UNIT=8,FILE='NEWSTAND.INI',STATUS='UNKNOWN')
      WRITE(2,1)
      WRITE(3,1)
      DO 100 J=1,NPAT
         DO 101 K=1,MAXIND
            IF(TAX(J,K).EQ.0)GOTO 100 !moved
       WRITE(8,2) TAX(J,K),DBH(J,K),HBC(J,K),LEA(J,K),AGE(J,K)
C           IF(TAX(J,K).EQ.0)GOTO 100
101         CONTINUE
100      CONTINUE
      CLOSE(UNIT=8)
      RETURN

* format statements

1     FORMAT(/' FINAL TREE ARRAY WRITTEN TO FILE NEWSTAND.INI')
2     FORMAT(1X,I4,F10.2,F10.2,F10.2,I8)

      END  ! SUBROUTINE OUT

****************************************************************************

      SUBROUTINE PRAND(U,N)
      IMPLICIT NONE

* used as is in all three versions - FORSKA2, CLIMATE, LANDSCAPE

* returns a random number N drawn from a Poisson distribution with
* expected value U. I is a seed for the random number generator

* subroutine arguments

      REAL U
      INTEGER N

* local variables
```

```
      REAL UTOP,P,R,Q
      PARAMETER(UTOP=88.0)

* function declarations

      REAL    RAND2

*DEBUG      write (*,*) u
      IF(U.GT.UTOP) THEN   ! STOP 'Failure in PRAND: expected value too high'
        write (*,*) 'Failure in PRAND: expected value too high'
        U = 75.0
      ENDIF

      P=EXP(-U)
      Q=P
      R=RAND2()
      N=0
100   IF(Q.GE.R)RETURN
      N=N+1
      P=P*U/N
      Q=Q+P
      GOTO 100

      END  ! SUBROUTINE PRAND

****************************************************************************

      SUBROUTINE IN(SYSOUT,NPAT,PTCAGE)
      IMPLICIT NONE

* FORSKA2, CLIMATE and LANDSCAPE
* reads an array to initialize the stand

*DTP 21 October 1998.
*    Changed Model configuration to allow more trees per plot. This has to be
*    fixed in all COMMON blocks. Put COMMONs into compar.h include files so
*    that these can be modified conveniently.

      INCLUDE 'compar.h'    ! global model parameters
      INCLUDE 'comtax.h'    ! species parameters
      INCLUDE 'comtree.h'   ! tree parameters

* subroutine arguments
      INTEGER SYSOUT,NPAT,PTCAGE(MAXPAT)

* local variables
      INTEGER J,K

      OPEN(UNIT=7,FILE='STAND.INI',STATUS='OLD',ERR=999)
      WRITE(SYSOUT,1)
      DO 100 J=1,NPAT
```

```
          PTCAGE(J)=0 ! Initialise patch age
          DO 101 K=1,MAXIND
             READ(7,*)TAX(J,K),DBH(J,K),HBC(J,K),LEA(J,K),AGE(J,K)
             IF(AGE(J,K).GT.PTCAGE(J)) PTCAGE(J) = AGE(J,K) ! Update patch age to
age of oldest trees
             IF(TAX(J,K).EQ.0)THEN
C              DO 102 K1=K,MAXIND
C                TAX(J,K1)=0
C102            CONTINUE
               write (sysout,105)
105            FORMAT ('*** Warning: TAX not filled')
               GOTO 100 ! Skip past end of this loop
             ENDIF
101          CONTINUE
100       CONTINUE
      CLOSE(UNIT=7)
      RETURN

* error message

999   WRITE(SYSOUT,2)
*DTP  PAUSE 'PRESS RETURN TO QUIT'
      STOP 'FORSKA TERMINATED BECAUSE OF READ ERROR(S).'

* format statements:

1     FORMAT(/' INITIAL TREE ARRAY READ FROM FILE STAND.INI')
2     FORMAT(/' ERROR...... File STAND.INI not found!')

      END  ! SUBROUTINE IN

*****************************************************************************

      SUBROUTINE CSKOT(J,DBH0)

* CLIMATE and LANDSCAPE version 89.10.28

*DTP 21 October 1998.
*    Changed Model configuration to allow more trees per plot. This has to be
*    fixed in all COMMON blocks. Put COMMONs into compar.h include files so
*    that these can be modified conveniently.

      INCLUDE 'compar.h'    ! global model parameters
      INCLUDE 'comtax.h'    ! species parameters
      INCLUDE 'comtree.h'   ! tree parameters
      INCLUDE 'comdead.h'   ! dead tree parameters


* function declarations

      REAL    RAND2
```

```
* local variables

      INTEGER J,K,L,M,T
      INTEGER NSPR(MAXIND)
      REAL DGE(MAXIND)
      LOGICAL SIZEOK


* scans through TAX looking for negative values

! Changed from K=2 to K=1, from IF(TAX(J,K).GT.0) to
! 100 IF(TAX(J,K).GE.0), and from 100 IF(TAX(J,K).EQ.0)RETURN to
! IF(TAX(J,K).EQ.0)RETURN.  SSamson 05/05/92

      K=1
100   IF(TAX(J,K).GE.0)THEN
         IF(TAX(J,K).EQ.0)RETURN
         K=K+1
      ELSE

* finds a tree that is flagged for removal. Relevant attributes
* of the dead tree are stored in case sprouting occurs, but
* sprouting will only be allowed if SIZEOK i.e. the dead tree was
* in the diameter range above SMN.

* Dimensions of dead trees are stored in DDBH, DAGE and DTAX.
* NUM gives the number of dead trees. DGE is the growth efficiency
* of the dead tree before it died (from TVXT) to be used in sprouting

         T=-TAX(J,K)
         NUM(J)=NUM(J)+1
         DTAX(J,NUM(J))=T
         DAGE(J,NUM(J))=AGE(J,K)
         DGE(NUM(J))=TGE(K)
         DDBH(J,NUM(J))=DBH(J,K)
         SIZEOK=(DBH(J,K).GE.SMN(T))

* removes the tree and shifts the array positions of higher-numbered
* trees to close the gaps in the array.

! In the loop below, when L=MAXIND, the program will attempt to copy
! the value of an array that is beyond the end of the array (ie. L+1
! or MAXIND+1 is beyond the end of the array.)  This loop must be
! changed to DO 101 L=K,MAXIND-1 and all varname(J,MAXIND) to 0.

! Note:  the above changes have been made.  It is also possible that
!        varname(J,MAXIND) is always 0.  This would prevent copying
!        values from beyond the end of the array.  SSamson 05/05/92

* TLS if individual being removed is last "K" in the list, "K" becomes zero
* after array shift. If IF(TAX(J,L).EQ.0)GOTO102 comes before and not after,
* this K=0 will be added to the list of individuals. Sprouts and saplings added
```

```
* after this point became when they reach the first K=0.

         DO 101 L=K,MAXIND-1
C          IF(TAX(J,L).EQ.0)GOTO102
            TAX(J,L)=TAX(J,L+1)
            DBH(J,L)=DBH(J,L+1)
            HBC(J,L)=HBC(J,L+1)
            AGE(J,L)=AGE(J,L+1)
            LEA(J,L)=LEA(J,L+1)
           IF(TAX(J,L).EQ.0)GOTO102
 101     CONTINUE

         TAX(J,MAXIND)=0
         DBH(J,MAXIND)=0.0
         HBC(J,MAXIND)=0.0
         AGE(J,MAXIND)=0
         LEA(J,MAXIND)=0.0

* the tree is now considered for possible sprouting. If it can sprout,
* plant a Poisson random number of sprouts using
* SPR (taxon) * TGE (of tree at death) = NSPR.

 102     IF((SPR(T).EQ.0.0).OR.(INC(J,T).EQ.0.0))GOTO100
         IF(SIZEOK)THEN
          X=SPR(T)*DGE(NUM(J))       !moved from argument list to debug
            CALL PRAND(X,NSPR(T))

           IF (NSPR(T).EQ.0) GOTO 100 ! TLS

            DO 103 M=L,L+NSPR(T)-1
               IF(M.GE.MAXIND)STOP 'too many trees in SKOT'
               TAX(J,M)=T
               DBH(J,M)=DBH0+RAND2()*INC(J,T)
               LEA(J,M)=LAC(T)*(DBH(J,M)**2)
               HBC(J,M)=0.0
               AGE(J,M)=0
103         CONTINUE
         ENDIF
      ENDIF
      GOTO 100

      END  ! SUBROUTINE CSKOT

*****************************************************************************
* A series of functions used in FORSKA2, CLIMATE and LANDSCAPE VERSIONS
*
      REAL FUNCTION HEIGHT(D,HM,S)

      REAL D,HM,S

* computes the height of a tree with diameter D, max height HM, and
* initial slope of diameter vs height S
```

```
      HEIGHT=1.3+((HM-1.3)*(1-EXP(-D*S/(HM-1.3))))!tls added extra bracket to
debug
      RETURN
      END  ! REAL FUNCTION HEIGHT

***********************************************************************

      REAL FUNCTION HDERIV(D,HM,S)

      REAL D,HM,S

* computes the derivative of height with respect to diameter for a tree
* with diameter D, max height HM, and initial slope of diameter vs height S

      HDERIV=S*EXP(-D*S/(HM-1.3))

      RETURN
      END  ! REAL FUNCTION HDERIV

***********************************************************************

      REAL FUNCTION DBHINC(X,D,HM,S)

      REAL X,D,HM,S,X1,X2

* function declarations

      REAL   HEIGHT,HDERIV

* computes diameter increment for a tree with growth
* ((diameter**2)*height) increment X, diameter D,
* max height HM, and initial slope of diameter vs height S

      X1=D*D*HDERIV(D,HM,S)
      X2=2*D*HEIGHT(D,HM,S)
      DBHINC=X/(X1+X2)

      RETURN
      END  ! REAL FUNCTION DBHINC

***********************************************************************

      REAL FUNCTION PDEATH(EFF,U0,U1,T,RHO,TIM)

      REAL EFF,U0,U1,T,RHO,X
      INTEGER TIM

* computes a probability of death on the basis of a tree's relative growth
* efficiency EFF, growth-independent mortality rate U0, zero-growth
* mortality rate U1, threshold relative growth efficiency T, steepness
* parameter R and timestep length TIM
```

```
* RHO determines the slope of the continuous function.
* If RHO is greater than 20 (to avoid numeric overflow on 16-bith systems),
* this function becomes a step function with the step at TDI

      IF(RHO.LE.20)THEN
         X=U0+U1/(1.+(EFF/T)**RHO)
      ELSE
         IF(EFF.LE.T)THEN
            X=U0+U1
         ELSE
            X=U0
         ENDIF
      ENDIF
      PDEATH=1.-EXP(-X*TIM)
      RETURN
      END  ! REAL FUNCTION PDEATH

***********************************************************************

      INTEGER FUNCTION MORT(PD)

      REAL PD,RAND2

* Trees are flagged for death with probability PD

      IF(RAND2().LT.PD)THEN
         MORT=-1
      ELSE
         MORT=1
      ENDIF
      RETURN

      END  ! INTEGER FUNCTION MORT

***********************************************************************

      REAL FUNCTION RAND2()

      INTEGER IE,IM,IG

* Algorithm as described in APPL. STATIST. 31:2 (1982)
* The function returns a pseudo-random number uniformly distributed
* between 0 and 1.

* IE, IM and IG should be set to integer values between
* 1 and 30000 before the first entry.

      COMMON /RANDOM/ IE,IM,IG
      IE=171*MOD(IE,177)-2* (IE/177)
      IM=172*MOD(IM,176)-35*(IM/176)
      IG=170*MOD(IG,178)-63*(IG/178)
```

```
      IF (IE.LT.0)IE=IE+30269
      IF (IM.LT.0)IM=IM+30307
      IF (IG.LT.0)IG=IG+30323

      RAND2=AMOD(FLOAT(IE) /30269.0+FLOAT(IM)/30307.0+
     +           FLOAT(IG) /30323.0,1.0)
      RETURN

      END  ! REAL FUNCTION RAND

*****************************************************************************

      SUBROUTINE CINIT(NUM)
      IMPLICIT NONE

* CLIMATE and LANDSCAPE version 89.10.24

*DTP 21 October 1998.
*    Changed Model configuration to allow more trees per plot. This has to be
*    fixed in all COMMON blocks. Put COMMONs into compar.h include files so
*    that these can be modified conveniently.

      INCLUDE 'compar.h'     ! global model parameters
      INCLUDE 'comrun.h'     ! settings for this run
      INCLUDE 'comsite.h'    ! site and climate variables
      INCLUDE 'comtax.h'     ! species parameters
      INCLUDE 'comtree.h'    ! tree parameters

* function declarations

      REAL DBHINC

* local variables

      INTEGER NUM(MAXPAT),I,J,K
      REAL    TLA,LAI,GSLITE,M4LITE,FA,P


* initializes max growth efficiency and max initial diameter increment
* for each species, limited only by above canopy light intensity (INS)
* computes total leaf area on the patch

* computes total leaf area on a patch

      DO 100 J=1,NPAT
         TLA=0.0
         DO 101 K=1,MAXIND
            IF(TAX(J,K).EQ.0)GOTO 102
            TLA=TLA+LEA(J,K)
101         CONTINUE
```

```
* computes leaf area index and light at the forest floor
* for both a growing and -4 season

102      LAI=TLA/PAT/1.E4
         GSLITE=EXP(-KCO*LAI)*XGSINS
         M4LITE=EXP(-KCO*LAI)*XM4INS

* computes growth increment for each species under these light conditions

         DO 103 I=1,NTAX

* checks to see if deciduous or evergreen

          IF(DORE(I).EQ.0)THEN
* deciduous
            IF(KCO*GSLITE.LT.LCP(I))THEN
               INC(J,I)=0.0
            ELSE
               P=GSC(I)*(KCO*GSLITE-LCP(I))/(KCO*GSLITE+ALP(I)-LCP(I))
               FA=LAC(I)*(DBH0**2)
               INC(J,I)=MAX(0.0,DBHINC(P*FA*TIM,DBH0,HMX(I),HDS(I)))
            ENDIF
          ELSE
* evergreen
            IF(KCO*M4LITE.LT.LCP(I))THEN
               INC(J,I)=0.0
            ELSE
               P=GSC(I)*(KCO*M4LITE-LCP(I))/(KCO*M4LITE+ALP(I)-LCP(I))
               FA=LAC(I)*(DBH0**2)
               INC(J,I)=MAX(0.0,DBHINC(P*FA*TIM,DBH0,HMX(I),HDS(I)))
            ENDIF
          ENDIF

103         CONTINUE
100      CONTINUE

* initializes the growth under optimal light conditions

      DO 200 I=1,NTAX

* deciduous or evergreen

       IF(DORE(I).EQ.0)THEN

         P=(KCO*XGSINS-LCP(I))/(KCO*XGSINS+ALP(I)-LCP(I))
         GOP(I)=GSC(I)*P*TIM

       ELSE

         P=(KCO*XM4INS-LCP(I))/(KCO*XM4INS+ALP(I)-LCP(I))
         GOP(I)=GSC(I)*P*TIM
       ENDIF
```

```
200      CONTINUE

* initializes the dead trees and production on each patch to zero

      DO 300 J=1,NPAT
         NUM(J)=0
         DO 301 I=1,NTAX
            PRO(J,I)=0.0
301         CONTINUE
300      CONTINUE

      RETURN
      END  ! SUBROUTINE CINIT

******************************************************************************

      SUBROUTINE CDEDST(SYSOUT,L,NX1,NX2,AREA,DW,DW1,BCF,HMX,HDS)
      IMPLICIT NONE

* CLIMATE and LANDSCAPE version 89.10.29

*DTP 21 October 1998.
*    Changed Model configuration to allow more trees per plot. This has to be
*    fixed in all COMMON blocks. Put COMMONs into compar.h include files so
*    that these can be modified conveniently.

      INCLUDE 'compar.h'     ! global model parameters
      INCLUDE 'comrun.h'     ! settings for this run
      INCLUDE 'comsite.h'    ! site and climate variables
      INCLUDE 'comnames.h'   ! species names
      INCLUDE 'comtree.h'    ! tree parameters
      INCLUDE 'comdead.h'    ! dead tree parameters

* subroutine arguments
      INTEGER NX1,NX2,L,SYSOUT
      REAL    AREA,DW(MAXSPE),DW1,DBMAS(MAXSPE)
      REAL    HMX(MAXSPE),HDS(MAXSPE),BCF(MAXSPE)

* local variables

      REAL    DCWDTH,HCWDTH,AGWDTH,P4
      INTEGER NCL
*      PARAMETER (NCL=24,DCWDTH=5.,HCWDTH=1.5,AGWDTH=10.0   )
      PARAMETER (NCL=50,DCWDTH=2.0,HCWDTH=1.5,AGWDTH=10.0   )

      CHARACTER*8 ALLT


* local variables

      INTEGER N1(NCL),N(MAXSPE,NCL),NN1(NCL),NN(MAXSPE,NCL),
```

```
     +        A1(NCL),A(MAXSPE,NCL),O1,O(MAXSPE)
      INTEGER I,J,K,M,NA,ICL,JCL,KCL,T
      REAL    D,H,HEIGHT,BASA,BIOM,B1,B(MAXSPE)
      REAL    AVTREE     ! DTP Added this to print out mean tree size

      DATA ALLT/'all taxa'/
      P4=ATAN(1.)


* initializes and computes for all dead trees: numbers of trees by diameter
* class and taxon (N) and by diameter class for all taxa (N1), comparable
* statistics for height classes (NN, NN1) and age classes (A,A1), basal area
* (cm**2) by taxon (B) and for all taxa (B1) , leaf area (m**2) by taxon (F)
* and for all taxa (F1), stemwood biomass (Mg) by taxon (DW) and for all
* taxa (DW1), total numbers of trees by taxon (O) and for all taxa (O1)

      DO 100 I=1,NTAX
100      DW(I)=0.0
      DW1=0.0

      IF(NX1.EQ.NX2.AND.START.LE.L*TIM)THEN
c         WRITE(3,1)NX1,TIM*L,TIM*LPR,('_',K=1,36)
         IF(NUM(NX1).EQ.0)THEN
            WRITE(3,6)
            RETURN
         ENDIF

      ELSEIF(NX2.EQ.NPAT.AND.NX1.EQ.1.AND.START.LE.L*TIM)THEN
c         WRITE(3,2)TIM*L,TIM*LPR,('_',K=1,30)
         DO 101 J=1,NPAT
            IF(NUM(J).EQ.0)GOTO 101
            GOTO 200
101         CONTINUE
         WRITE(3,6)
         RETURN
      ENDIF


200   B1=0.0
      O1=0
      DO 201 I=1,NTAX
         B(I)=0.0
         O(I)=0
201      CONTINUE

      DO 202 M=1,NCL
         N1(M)=0
         NN1(M)=0
         A1(M)=0
         DO 203 I=1,NTAX
            N(I,M)=0
            NN(I,M)=0
```

```
            A(I,M)=0
203         CONTINUE
202      CONTINUE

      DO 300 J=NX1,NX2
         DO 301 K=1,NUM(J)
             T=DTAX(J,K)
             D=DDBH(J,K)
             H=HEIGHT(D,HMX(T),HDS(T))
             NA=DAGE(J,K)
             ICL=INT(D/DCWDTH)+1
             IF(ICL.GT.NCL)ICL=NCL
             JCL=INT(H/HCWDTH)+1
             IF(JCL.GT.NCL)JCL=NCL
             KCL=INT(NA/AGWDTH)+1
             IF(KCL.GT.NCL)KCL=NCL
             N(T,ICL)=N(T,ICL)+1
             NN(T,JCL)=NN(T,JCL)+1
             A(T,KCL)=A(T,KCL)+1
             N1(ICL)=N1(ICL)+1
             NN1(JCL)=NN1(JCL)+1
             A1(KCL)=A1(KCL)+1
             BASA=P4*D*D
             BIOM=D*D*H*BCF(T)/1.E3
             B(T)=B(T)+BASA
             DW(T)=DW(T)+BIOM
             B1=B1+BASA
             DW1=DW1+BIOM
             O(T)=O(T)+1
             O1=O1+1
301          CONTINUE

300       CONTINUE


* writes all aspects of the stand description for dead trees
* write to screen and FORCLI.out - dead tree information.
* basal area, biomass and  density for each period

      IF(START.LE.TIM*L)THEN
C         CALL DISTR(NCL,DCWDTH,' CM DBH ',NTAX,N,N1)
C         CALL DISTR(NCL,HCWDTH,'M HEIGHT',NTAX,NN,NN1)
C         CALL DISTR(NCL,AGWDTH,'YEAR AGE',NTAX,A,A1)

*DTP--   WRITE(SYSOUT,7)TIM*L,TIM*LPR
         WRITE(3,7)TIM*L,TIM*LPR
         DO 400 I=1,NTAX
            B(I)=B(I)/(1E+04 * AREA)
            DBMAS(I)=DW(I)/(AREA)
            O(I)=INT(O(I)/AREA)
```

```
*DTP--      WRITE(SYSOUT,8)NAM(I),O(I),B(I),DW(I),1000*DW(I)/
            WRITE(3,8)NAM(I),O(I),B(I),DBMAS(I)    ! species, # dead trees, basal
area, stemwood biomass

* DTP write dead tree info (BA, Biomass, Density, Mean tree kg) to DEDTREES.DAT
            IF(O(I).GT.0)THEN
              AVTREE=1000*DW(I)/O(I)
            ELSE
              AVTREE=0.0
            ENDIF

            write(19,20)L*TIM,NAM(I),B(I),DBMAS(I),O(I),AVTREE

400         CONTINUE
      ENDIF

      RETURN

* format statements:
1     FORMAT(/' DESCRIPTION OF PATCH',I4,' AFTER',I6,' YEARS _____'
     + ,' Trees which died during the last',I6,' years ',36A1/)
2     FORMAT(/' DESCRIPTION OF THE TOTAL STAND AFTER',I6,' YEARS __'
     + ,'___ Trees which died during the last',I6,' years ',30A1/)
3     FORMAT(1X)
4     FORMAT(11X,'DENSITY (/HA)    BA (M**2/HA)   BIOMASS (MG/HA)'/)
5     FORMAT(1X,A8,F12.0,F14.1,F14.1)
6     FORMAT(/1X,'No trees died during this period.')
7     FORMAT(/' STAND AFTER',I6,' YEARS - trees that died
     + in the last',I6,' years')
c   8     FORMAT(X,A8,2X,'TOTAL ',F8.3,2X,'BASALA ',F8.3,2X,'BIOMAS ',F8.3)
8     FORMAT(X,A8,2X,'TOTAL ',I8,2X,'BASALA ',F8.3,2X,'BIOMAS ',F8.3)
20    FORMAT(X,I5,X,A8,2(X,F12.3),X,I7,X,F12.3)

      END  ! SUBROUTINE CDEDST

*****************************************************************************

      SUBROUTINE CLIMEF(SYSOUT,L)
      IMPLICIT NONE

* CLIMATE and LANDSCAPE version 89.10.29
* written by Martin Sykes and Colin Prentice 1990

* computes the growth multipliers.
* checks to see if GDD, temp coldest month below minimum for species
* if so multipliers = 0 else equals 1.
* computes drought effect multipliers as per ICP
* sets max.temp of coldest month multiplier to 0 or 1 for ESTBL routine
* checks if warmest month exceeds species limit
* averages light intensity (INS) over time step.
```

```
*DTP 21 October 1998.
*    Changed Model configuration to allow more trees per plot. This has to be
*    fixed in all COMMON blocks. Put COMMONs into compar.h include files so
*    that these can be modified conveniently.

      INCLUDE 'compar.h'     ! global model parameters
      INCLUDE 'comrun.h'     ! settings for this run
      INCLUDE 'comsite.h'    ! site and climate variables
      INCLUDE 'comtax.h'     ! species parameters
      INCLUDE 'comtree.h'    ! tree parameters
      INCLUDE 'comdead.h'    ! dead tree parameters

* local variables

      INTEGER I,J,K,L,SYSOUT
      REAL TOTGDD,TGSDRT,TM4DRT,TGSINS,TM4INS,TTCOLD,TTWARM,TTCO2,XGDD,
     %     XGSDRT,XM4DRT,XTCOLD,XTWARM,XTCO2

* gives growth multiplier for each species to be applied in subroutine
* TVXT or ETBL - growing degree days, growing/-4 drought index, temps.

* initialise totals

      TOTGDD=0.0
      TGSDRT=0.0
      TM4DRT=0.0
      TGSINS=0.0
      TM4INS=0.0
      TTCOLD=0.0
      TTWARM=0.0
      TTCO2=0.0

*      IF(L.EQ.1)K=1          ! DTP added this fix. Surely K is undefined if L<>1
?
      K = L*TIM - TIM + 1

* average each index over the time step

      DO 100 J=K,L*TIM
        TOTGDD=TOTGDD+GDD(J)
        TGSDRT=TGSDRT+GSDRI(J)
        TM4DRT=TM4DRT+M4DRI(J)
        TGSINS=TGSINS+GSINS(J)
        TM4INS=TM4INS+M4INS(J)
        TTCOLD=TTCOLD+TCOLD(J)
        TTWARM=TTWARM+TWARM(J)
        TTCO2 =TTCO2+ADDCCP(J)

c      write(3,800)tgsins,tm4ins,ttwarm,gsins(j),m4ins(j),twarm(j),j,k,
c     %             l,tim

c800   format(X,f6.2,1x,f6.2,1x,f6.2,1x,f6.2,1x,f6.2,xf6.2,i2,i2,i3,i3)
```

```
100     CONTINUE

* the local variable K is updated for the next timeperiod

      K=K+TIM

      XGDD=TOTGDD/TIM
      XGSDRT=TGSDRT/TIM
      XM4DRT=TM4DRT/TIM
      XGSINS=TGSINS/TIM     ! XGSINS = annual growing season dpar DTP 92/04/29
      XM4INS=TM4INS/TIM
      XTCOLD=TTCOLD/TIM
      XTWARM=TTWARM/TIM
      XTCO2 =TTCO2/TIM

* write heading for multipliers
c
        WRITE(SYSOUT,5)L*TIM
        WRITE(3,5)L*TIM
        WRITE(SYSOUT,10)
        WRITE(3,10)


      DO 101 I=1,NTAX

* set multipliers to 1 before checking on environment

       GDDMX(I)=1.0
       TCMX(I)=1.0
       TWMX(I)=1.0
       TWARMX(I)=1.0

**********************************************************************
* DTP 12 Dec 1995. Modification to soil water equations implemented
**********************************************************************

* check to see is a deciduous species

       IF(DORE(I).EQ.0)THEN
*        DRMX(I)=1-((XGSDRT/DRI(I))**2)
        DRMX(I)=1-((1.6667*XGSDRT/(DRI(I))-0.792*DRI(I))**2)
         IF(DRMX(I).LT.0.0)DRMX(I)=0.0

       ELSE

* must be an evergreen

*       DRMX(I)=1-((XM4DRT/DRI(I))**2)
        DRMX(I)=1-((1.6667*XM4DRT/DRI(I)-0.792*DRI(I))**2)
         IF(DRMX(I).LT.0.0)DRMX(I)=0.0
```

```
       ENDIF
**********************************************************************
* work out CO2 multiplier using present CO2 of 330 ppm

       IF(SWCO2.EQ.1)THEN
         CO2MX(I)=1+((FCO2*XTCO2)/((FCO2*330)-CCP(I)))

       ELSE
         CO2MX(I)=1.0

       ENDIF

* check if environment exceeds species limits - step functions
* if so set multiplier to zero

       IF(XGDD.LT.MINGDD(I))GDDMX(I)=0.0
       IF(XTCOLD.LT.MINTC(I))TCMX(I)=0.0
       IF(XTCOLD.GT.MAXTC(I))TWMX(I)=0.0
       IF(XTWARM.LT.MINTW(I))TWARMX(I)=0.0

* write out to screen and forcli.out multipliers for each species
* keep these commented as they use a lot of paper


C        WRITE(SYSOUT,15)NAM(I),GDDMX(I),DRMX(I),TCMX(I),TWMX(I),
C     %                         TWARMX(I),CO2MX(I),MUTMX(I,L),SAPRES(I,L),
C     %                         TFTMX(I,L)
C        WRITE(3,15)NAM(I),GDDMX(I),DRMX(I),TCMX(I),TWMX(I),
C     %                         TWARMX(I),CO2MX(I),MUTMX(I,L),SAPRES(I,L),
C     %                         TFTMX(I,L)

c        WRITE(SYSOUT,15)GDDMX(I),DRMX(I),TCMX(I),TWMX(I),TWARMX(I)
c        WRITE(3,15)GDDMX(I),DRMX(I),TCMX(I),TWMX(I),TWARMX(I)

101   CONTINUE


      RETURN
* format statements
5     FORMAT(/20X,'Growth multipliers etc after 'I4,'years'/)
10    FORMAT(X,'Species',3X,'Gdd ',3X,'Drmx',3X,'TC-c',3X,
     %'TC-w'3X,'TW-c'3X,'CO2mx',2x,'Mutmx'2X,'SapRes',X,'Therm'/)
c 15    FORMAT(X,A8,X,F6.3,X,F6.3,X,F6.3,X,F6.3,X,F6.3,X,F6.3,X,F6.3,X,
c     %      F6.3,X,F6.3)
15    FORMAT(X,F6.3,X,F6.3,X,F6.3,X,F6.3,X,F6.3)


      END  ! SUBROUTINE CLIMEF
```

```
******************************************************************************

      SUBROUTINE PLTOUT (NTAX,NPAT,NAME,PAT,PTCAGE,TAX,DORE,INTVL)

* Writes out stand indices: Age, Biomass, BA, Density and Productivity for
* each plot, by species, including softwood and hardwood totals and plot
* totals, at each stand description interval.  The data are written to a
* a big file array - over 600 lines and approximately 110 elements across.
* Elements are separated by commas to facilate loading into Microsoft Excel.

* Productivity for plot I, sp. J is calculated as the difference [current
* biomass, PBIOM(I,J) minus previous biomass, PPROD(I,J)] divided by the
* stand description interval, unless the current species maximum age is less
* than the stand description interval, in which case, take the current
* accumulated biomass divided by the age.  If the age is 0 (which would
* cause a DIV/0 error), set PPROD(I,J) to zero.

* Values of plot biomass, basal area, LAI, stem density and productivity
* are also sorted by age class in arrays PBIOM1, PBASA1, PLAI1, PDENS1 and
* PPROD1, with the numbers of plots in each age class accumulated in the
* array PLTACL.  The number of age classes is determined by parameter
* MAXACL, and the width of the age class (i.e. number of years) by AGEINT.

      IMPLICIT NONE

*DTP 21 October 1998.
*    Changed Model configuration to allow more trees per plot. This has to be
*    fixed in all COMMON blocks. Put COMMONs into compar.h include files so
*    that these can be modified conveniently.

      INCLUDE 'compar.h'    ! global model parameters
      INCLUDE 'comsite.h'   ! site and climate variables
      INCLUDE 'complot.h'  ! plot output parameters


* Local variables
      INTEGER AGEINT
      PARAMETER (AGEINT=10)
      CHARACTER*8 NAME(MAXSPE)
      INTEGER NTAX,NPAT,PTCAGE(MAXPAT),TAX(MAXPAT,MAXIND),
     +        INTVL,DORE(MAXSPE)
      REAL    PAT

      INTEGER I,J,AGECL,SDSOFT,SDHARD
      REAL    BMSOFT,BMHARD,BASOFT,BAHARD,LASOFT,LAHARD,
     +        PDSOFT,PDHARD

      DO I=1,NPAT
         BMHARD=0.0
         BAHARD=0.0
         LAHARD=0.0
         SDHARD=0
```

```
         PDHARD=0.0
         BMSOFT=0.0
         BASOFT=0.0
         LASOFT=0.0
         SDSOFT=0
         PDSOFT=0.0
         AGECL=MIN(INT(PTCAGE(I)/AGEINT)+1,MAXACL+1)
         PLTACL(AGECL)=PLTACL(AGECL)+1
         DO J=1,NTAX
            IF(TAXAGE(I,J).GE.INTVL) THEN
               PPROD(I,J)=(PBIOM(I,J)-PPROD(I,J))/INTVL     ! Mean prody Mg/yr
            ELSEIF(TAXAGE(I,J).GT.0) THEN
               PPROD(I,J)=PBIOM(I,J)/MIN(1,TAXAGE(I,J))
            ELSE
               PPROD(I,J)=0.0
            ENDIF

* DTP 96/12/03: These conversions done more efficiently outside loop (see below)
*            PBIOM(I,J)=10*PBIOM(I,J)                     ! Convert to t/ha
*            PBASA(I,J)=PBASA(I,J)/1E4                    ! Convert to m2/ha
*            PLAI(I,J)=PLAI(I,J)/(PAT*1E4)                ! Convert to m2/m2
*            PDENS(I,J)=10*PDENS(I,J)                     ! Convert to stem/ha
*            PPROD(I,J)=0.01*PPROD(I,J)                   ! Convert to t/ha/yr
            PBIOM1(J,AGECL)=PBIOM1(J,AGECL)+PBIOM(I,J)   ! Total biomass for sp.
J in age class AGECL
            PBASA1(J,AGECL)=PBASA1(J,AGECL)+PBASA(I,J)   ! Total BA for sp. J in
age class AGECL
            PLAI1(J,AGECL)=PLAI1(J,AGECL)+PLAI(I,J)      ! Total Leaf area for
sp. J in age class AGECL
            PDENS1(J,AGECL)=PDENS1(J,AGECL)+PDENS(I,J)   ! Total Stems for sp. J
in age class AGECL
            PPROD1(J,AGECL)=PPROD1(J,AGECL)+PPROD(I,J)   ! Total prody for sp. J
in age class AGECL


            IF(DORE(J).EQ.0) THEN
               BMHARD=BMHARD+PBIOM(I,J)                  ! Total hardwood biomass
etc. for patch I...
               BAHARD=BAHARD+PBASA(I,J)
               LAHARD=LAHARD+PLAI(I,J)
               SDHARD=SDHARD+PDENS(I,J)
               PDHARD=PDHARD+PPROD(I,J)
            ELSE
               BMSOFT=BMSOFT+PBIOM(I,J)                  ! Total softwood biomass
etc. for patch I...
               BASOFT=BASOFT+PBASA(I,J)
               LASOFT=LASOFT+PLAI(I,J)
               SDSOFT=SDSOFT+PDENS(I,J)
               PDSOFT=PDSOFT+PPROD(I,J)
            ENDIF
         ENDDO ! J = 1,NTAX
```

```
* Print indicators for patch I....
         WRITE (21,10) I,PTCAGE(I),          ! Total Biomass, by sp., hardwood,
softwood, total (t/ha)
     +          (10*PBIOM(I,J),J=1,NTAX),10*BMHARD,10*BMSOFT,
     +          10*(BMHARD+BMSOFT)
         WRITE (22,10) I,PTCAGE(I),          ! Total Basal Area, by sp.,
hardwood, softwood, total (m2/ha)
     +          (10*PBASA(I,J)/1E4,J=1,NTAX),10*BAHARD/1E4,10*BASOFT/1E4,
     +          10*(BAHARD+BASOFT)/1E4
c    +          (PBASA(I,J)/1E4,J=1,NTAX),BAHARD/1E4,BASOFT/1E4,
c     +          (BAHARD+BASOFT)/1E4
         WRITE (23,10) I,PTCAGE(I),          ! Mean Leaf Area Index, by sp.,
hardwood, softwood, total (m2/m2)
     +          (PLAI(I,J)/(PAT*1E4),J=1,NTAX),LAHARD/(PAT*1E4),
     +          LASOFT/(PAT*1E4),(LAHARD+LASOFT)/(PAT*1E4)
         WRITE (24,11) I,PTCAGE(I),          ! Total Stem density, by sp.,
hardwood, softwood, total (stem/ha)
     +          (10*PDENS(I,J),J=1,NTAX),10*SDHARD,10*SDSOFT,
     +          10*(SDHARD+SDSOFT)
         WRITE (25,12) I,PTCAGE(I),          ! Mean Prody., by sp., hardwood,
softwood, total (t/ha/yr)
     +          (10*PPROD(I,J),J=1,NTAX),10*PDHARD,10*PDSOFT,
     +          10*(PDHARD+PDSOFT)

* Record last additions for current patch to age-class totals for
* hardwoods and softwoods, respectively
         PBIOM1(MAXSPE+1,AGECL)=PBIOM1(MAXSPE+1,AGECL)+BMHARD*10
         PBASA1(MAXSPE+1,AGECL)=PBASA1(MAXSPE+1,AGECL)+(10*BAHARD/1E4)
         PLAI1(MAXSPE+1,AGECL)=PLAI1(MAXSPE+1,AGECL)+LAHARD/(PAT*1E4)
         PDENS1(MAXSPE+1,AGECL)=PDENS1(MAXSPE+1,AGECL)+SDHARD*10
         PPROD1(MAXSPE+1,AGECL)=PPROD1(MAXSPE+1,AGECL)+PDHARD*10

         PBIOM1(MAXSPE+2,AGECL)=PBIOM1(MAXSPE+2,AGECL)+BMSOFT*10
         PBASA1(MAXSPE+2,AGECL)=PBASA1(MAXSPE+2,AGECL)+(10*BASOFT/1E4)
         PLAI1(MAXSPE+2,AGECL)=PLAI1(MAXSPE+2,AGECL)+LASOFT/(PAT*1E4)
         PDENS1(MAXSPE+2,AGECL)=PDENS1(MAXSPE+2,AGECL)+SDSOFT*10
         PPROD1(MAXSPE+2,AGECL)=PPROD1(MAXSPE+2,AGECL)+PDSOFT*10
      ENDDO

* Update PPROD to current values of PBIOM - for prody calculations at next
* stand description.
      DO I=1,NPAT
        DO J=1,NTAX
          PPROD(I,J)=PBIOM(I,J)
        ENDDO
      ENDDO

   10 FORMAT(2(I4,','),<NTAX>(F6.2,','),2(F7.2,','),F7.2)
   11 FORMAT(2(I4,','),<NTAX>(I6,','),2(I7,','),I7)
   12 FORMAT(2(I4,','),<NTAX>(F6.3,','),2(F7.3,','),F7.3)

      END  ! SUBROUTINE PLTOUT
```

```
*****************************************************************************

      SUBROUTINE DBHOUT (NAME,PTCAGE,DORE,INTVL,T)

* Writes out DBH distribution for MAXDCL DBH classes of DBHINT cm width,
* for each species, for softwoods and hardwoods and total stand, for
* each of up to MAXPAT plots, at each stand description interval.  The data
* are written to an array - over 600 lines, by 28 elements across.
* Elements are separated by commas to facilate loading into Microsoft Excel.

* Values of indvidual tree DBHs contained in DBHDAT (MAXPAT,MAXSPE,NCL) are
* sorted into DBH classes in array DBHCLS(MAXPAT,MAXSPE). The number of DBH
* classes is determined by parameter NCL, and the width of the DBH classes
* (i.e. range of DBH's in cm) by DCWDTH.

      IMPLICIT NONE

*DTP 21 October 1998.
*     Changed Model configuration to allow more trees per plot. This has to be
*     fixed in all COMMON blocks. Put COMMONs into compar.h include files so
*     that these can be modified conveniently.

      INCLUDE 'compar.h'    ! global model parameters
      INCLUDE 'comrun.h'    ! settings for this run
      INCLUDE 'comtree.h'   ! tree parameters

* subroutine arguments
      INTEGER DORE(MAXSPE)       !TLS added (MAXSPE) to debug

* Local variables
      INTEGER NCL, TNTREE
      REAL    DCWDTH,RESULT

**********************************************************************
* DTP 99/06/24: Changed these for Pingree Park Experiment
*      PARAMETER (NCL=50, DCWDTH=2.0)

      PARAMETER (NCL=31, DCWDTH=5.0)

***********************************************************************

      CHARACTER*8 NAME(MAXSPE)

      INTEGER PTCAGE(MAXPAT), ! TAX(MAXPAT,MAXIND),
     +        INTVL,T
*      INTEGER*4 DBHCLS(MAXSPE,NCL)
      REAL DBHCLS(MAXSPE,NCL)

      INTEGER I,J,K,DBSOFT,DBHARD,TOTAL

***********************************************************************
```

```
* DTP 99/06/24: Changed these for Pingree Park Experiment
*     WRITE (26,20)(NINT(DCWDTH*K),K=1,NCL)

      WRITE (26, 505)
 505  FORMAT ('\tClass\tABBA_#\tBEPA_#\tLALA_#\tPIGL_#\tPIMA_#\t',
     >        'PIBA_#\tPIST_#\tPOBA_#\tPOTR_#\tTHOC_#\tOTHR_#')

***********************************************************************
      TNTREE  = 0  ! Count total number of live trees in forest

      DO K=1,NCL                  ! Loop through all DBH classes
         DO T = 1,NTAX+1          ! Loop through all species
             DBHCLS(T,K)=0        ! Initialise count for each species size class
         ENDDO
      ENDDO
      DO I=1,NPAT                    ! Loop through all patches
         DBHARD=0                    ! Initialise total for hardwoods
         DBSOFT=0                    ! Initialise total for softwoods
         DO J=1,MAXIND               ! Loop through all trees in patch I
            T=TAX(I,J)               ! Get species of this tree
            IF(T.GT.NTAX) T=NTAX+1   ! In case we have other species ??? this
won't work
            IF(T.GT.0)THEN           ! Tree is alive so include it
                                     ! (Don't include dead trees)
               TNTREE = TNTREE + 1

               RESULT = DBH(I,J)/DCWDTH
               K = INT(RESULT) + 1

               IF(K.GT.NCL) K=NCL            ! If K > num size classes, put tree
in the biggest size class
               DBHCLS(T,K)=DBHCLS(T,K)+1     ! Increment the count for this size
class

*               write(*,*) 'Class: ', K, '   DBH: ', DBH

               IF(DORE(T).EQ.1)THEN          ! If deciduous
                 DBHARD=DBHARD+1             !   include in hardwood count
               ELSE                          ! evergreen
                 DBSOFT=DBSOFT+1             !   include in softwood count
               ENDIF  ! IF(DORE(T) == 1)
            ENDIF  ! IF(T > 0)
         ENDDO  ! J = 1,MAXIND

         TOTAL=DBSOFT+DBHARD

***********************************************************************
* DTP 99/06/24: Changed these for Pingree Park Experiment
* Print DBH distribution for patch I....
*         WRITE (26,10) I,PTCAGE(I),          ! Total stems by sp., hardwood,
softwood, total (stem/ha)
```

```
*     +          (DBHCLS(K),K=1,NCL),TOTAL

      ENDDO ! I = 1,NPAT

      write(*,*) 'Total trees in forest = ', TNTREE

      DO K = 1,NCL          ! Print out stand structure in stem ha-1 (dbh class)-1
         IF(K.GE.NCL) THEN ! Last class includes all trees bigger than the start
of the last interval
*              WRITE (26, 507) (K-1)*5, (10*DBHCLS(T,K)/NPAT,T=1,NTAX+1)
             WRITE (26, 507) (10*DBHCLS(T,K)/NPAT,T=1,NTAX+1)
         ELSE  ! K < NCL   ! All other classes are centred on the midpoint of the
interval
             WRITE (26, 506) K*5-2.5, (10*DBHCLS(T,K)/NPAT,T=1,NTAX+1)
        ENDIF
      ENDDO

 506  FORMAT (F6.1,'\t', <NTAX>(F8.2,'\t'),F8.2)
* 507  FORMAT ('\t>', F5.0,'\t', <NTAX>(F8.2,'\t'),F8.2)
 507  FORMAT ('\t>150.\t', <NTAX>(F8.2,'\t'),F8.2)


  10  FORMAT(2(I4,','),<NCL>(I4','),I3)
  20  FORMAT('PAT#,AGE,',<NCL>(I4','),'TOTAL')

      END  ! SUBROUTINE DBHOUT

*****************************************************************************

      SUBROUTINE BYAGE (NAME,PTCAGE,TAX,DORE)

      IMPLICIT NONE

*DTP 21 October 1998.
*    Changed Model configuration to allow more trees per plot. This has to be
*    fixed in all COMMON blocks. Put COMMONs into compar.h include files so
*    that these can be modified conveniently.

      INCLUDE 'compar.h'    ! global model parameters
      INCLUDE 'comrun.h'    ! settings for this run
      INCLUDE 'complot.h'  ! plot output parameters

* subroutine arguments
      INTEGER PTCAGE(MAXPAT),TAX(MAXPAT,MAXIND),
     +        DORE(MAXSPE)
      CHARACTER*8 NAME(MAXSPE)

* Local variables
      INTEGER I,J,AGEINT
      PARAMETER (AGEINT=10)
```

```
* This routine takes the totals of single species estimates of biomass, basal
area
* Divide all totals by the number of plots*taxa represented in the age class
* for all species, plus all hardwoods, all softwoods and totals

* 27 September 1996: Need to watch for divide-by-zero errors here.
      DO J=1,MAXACL+1
         IF(PLTACL(J).GT.0)THEN
            DO I=1,NTAX
               PBIOM1(I,J)=PBIOM1(I,J)/PLTACL(J)                 ! Average sp. J
biomass by age classes
               PBASA1(I,J)=PBASA1(I,J)/PLTACL(J)                 ! Average sp. J
basal area by age classes
               PLAI1(I,J)=PLAI1(I,J)/PLTACL(J)                   ! Average sp. J
LAI by age classes
               PDENS1(I,J)=INT(PDENS1(I,J)/PLTACL(J))            ! Average sp. J
stem density by age classes
               PPROD1(I,J)=PPROD1(I,J)/PLTACL(J)                 ! Average sp. J
productivity by age classes
            ENDDO

            DO I=MAXSPE+1,MAXSPE+2                 ! Do averaging for hardwoods,
softwoods and totals
               PBIOM1(I,J)=PBIOM1(I,J)/PLTACL(J)                 ! Average
biomass by age classes
               PBASA1(I,J)=PBASA1(I,J)/PLTACL(J)                 ! Average basal
area by age classes
               PLAI1(I,J)=PLAI1(I,J)/PLTACL(J)                   ! Average LAI by
age classes
               PDENS1(I,J)=INT(PDENS1(I,J)/PLTACL(J))            ! Average stem
density by age classes
               PPROD1(I,J)=PPROD1(I,J)/PLTACL(J)                 ! Average
productivity by age classes
            ENDDO
         ELSE ! (PLTACL(J).EQ.0)
            DO I=MAXSPE+1,MAXSPE+2                 ! Zero out averages for age-
classes not represented
               PBIOM1(I,J)=0.0
               PBASA1(I,J)=0.0
               PLAI1(I,J)=0.0
               PDENS1(I,J)=0
               PPROD1(I,J)=0.0
            ENDDO
         ENDIF
      ENDDO

      DO J=1,MAXACL+1
         WRITE (21,10) (J-1)*AGEINT,J*AGEINT,PLTACL(J),
     +         (PBIOM1(I,J),I=1,NTAX),
     +          PBIOM1(MAXSPE+1,J),PBIOM1(MAXSPE+2,J),
     +          PBIOM1(MAXSPE+1,J)+PBIOM1(MAXSPE+2,J)
         WRITE (22,10) (J-1)*AGEINT,J*AGEINT,PLTACL(J),
```

```
     +         (PBASA1(I,J)/1E4,I=1,NTAX),
     +          PBASA1(MAXSPE+1,J),PBASA1(MAXSPE+2,J),
     +          PBASA1(MAXSPE+1,J)+PBASA1(MAXSPE+2,J)
         WRITE (23,10)  (J-1)*AGEINT,J*AGEINT,PLTACL(J),
     +         (PLAI1(I,J),I=1,NTAX),
     +          PLAI1(MAXSPE+1,J),PLAI1(MAXSPE+2,J),
     +          PLAI1(MAXSPE+1,J)+PLAI1(MAXSPE+2,J)
         WRITE (24,11)  (J-1)*AGEINT,J*AGEINT,PLTACL(J),
     +         (PDENS1(I,J),I=1,NTAX),
     +          PDENS1(MAXSPE+1,J),PDENS1(MAXSPE+2,J),
     +          PDENS1(MAXSPE+1,J)+PDENS1(MAXSPE+2,J)
         WRITE (25,10)  (J-1)*AGEINT,J*AGEINT,PLTACL(J),
     +         (PPROD1(I,J),I=1,NTAX),
     +          PPROD1(MAXSPE+1,J),PPROD1(MAXSPE+2,J),
     +          PPROD1(MAXSPE+1,J)+PPROD1(MAXSPE+2,J)
      ENDDO

* Now re-initialise the variables PBIOM1,PBASA1 etc. for next summary
      DO J=1,MAXACL+1
         DO I=1,NTAX
            PBIOM1(I,J)=0.0
            PBASA1(I,J)=0.0
            PLAI1(I,J)=0.0
            PDENS1(I,J)=0
            PPROD1(I,J)=0.0
         ENDDO
         DO I=MAXSPE+1,MAXSPE+2
            PBIOM1(I,J)=0.0
            PBASA1(I,J)=0.0
            PLAI1(I,J)=0.0
            PDENS1(I,J)=0
            PPROD1(I,J)=0.0
         ENDDO
         PLTACL(J)=0
      ENDDO

 10   FORMAT('="'I3,'-',I3,'"','I5,',',<NTAX>(F7.3,','),2(F7.3,','),F7.3)
 11   FORMAT('="'I3,'-',I3,'"','I5,',',<NTAX>(I6,','),2(I7,','),I7)

      END  ! SUBROUTINE BYAGE

******************************************************************************

      SUBROUTINE CSTAND(SYSOUT,L,BCF,HMX,HDS,PRO,DORE,PTCAGE)
      IMPLICIT NONE

* CLIMATE and LANDSCAPE version 89.10.29

*DTP 21 October 1998.
*    Changed Model configuration to allow more trees per plot. This has to be
*    fixed in all COMMON blocks. Put COMMONs into compar.h include files so
*    that these can be modified conveniently.
```

```
      INCLUDE 'compar.h'     ! global model parameters
      INCLUDE 'comrun.h'     ! settings for this run
      INCLUDE 'comsite.h'    ! site and climate variables
      INCLUDE 'comnames.h'   ! species names
      INCLUDE 'comtree.h'    ! tree parameters
      INCLUDE 'comdead.h'    ! dead tree parameters
      INCLUDE 'complot.h'  ! plot output parameters

* Subroutine arguments
*DTP -- I added these so that they can be passed from MAIN to PLTOUT
      INTEGER SYSOUT,L,PTCAGE(MAXPAT),DORE(MAXSPE)
      REAL    HMX(MAXSPE),HDS(MAXSPE),BCF(MAXSPE),PRO(MAXPAT,MAXSPE)


* local variables

      INTEGER NCL
      REAL    DCWDTH,HCWDTH,AGWDTH,AREA,P4
*      PARAMETER (NCL=24,DCWDTH=5.0,HCWDTH=1.5,AGWDTH=10.0)
      PARAMETER (NCL=50,DCWDTH=2.0,HCWDTH=1.5,AGWDTH=10.0)

      INTEGER N1(NCL),NN1(NCL),IA1(NCL)
      INTEGER N(MAXSPE,NCL),NN(MAXSPE,NCL),IA(MAXSPE,NCL)
      INTEGER NX1,NX2,I,J,K,M,T,ICL,JCL,KCL
      INTEGER AMN(MAXSPE),AMX(MAXSPE)
      REAL    D,LF,H,HEIGHT,BASA,BIOM,H1
      REAL    BHMN(MAXSPE),BHMX(MAXSPE),HMAX(MAXSPE)
      REAL    B1,F1,W1,P0,DW1,B(MAXSPE),F(MAXSPE)
      REAL    W(MAXSPE),P(MAXSPE)
      REAL    C(MAXPAT,MAXSPE),Q(MAXSPE),DW(MAXSPE)
      INTEGER O1,O(MAXSPE)

      real    avtree    ! DTP Added this to calculate average tree size

***********************************************************************
* DTP 99/06/24: Changed these for Pingree Park Experiment
      REAL    TOTLAI


      CHARACTER*8 ALLT
      DATA ALLT/'all taxa'/
      P4=ATAN(1.)

* initializes and computes: numbers of trees by diameter class and taxon
* (N) and by diameter class for all taxa (N1), comparable statistics for
* height classes (NN, NN1), basal area (cm**2) by taxon (B) and for all
* taxa (B1), leaf area (m**2) by taxon (F) and for all taxa (F1), stemwood
* biomass (Mg) by taxon (W) and for all taxa (W1), total numbers of
* trees by taxon (O) and for all taxa (O1), total stemwood production
* during the previous time interval by taxon (P) and for all taxa (P0), max
* and min bole height by taxon (H) and for all taxa (H1) and max and
```

```
* min dimensions of trees.

      TOTLAI = 0.0                  ! Initialise Total LAI

      IF(WPAT.EQ.0)THEN             ! No separate description of patches
         AREA=PAT*NPAT              ! Total simulated stand area in ha
         NX1=1
         NX2=NPAT                   ! But... what if NPAT = 1???
         GOTO 101
      ELSE                          ! print out data on separate patches
         NX1=0
         NX2=0
         AREA=PAT
      ENDIF

100   NX1=NX1+1
      NX2=NX2+1
      IF(NX1.GT.NPAT)THEN
         AREA=PAT*NPAT              ! Total simulated stand area in ha
         NX1=1
         NX2=NPAT
      ENDIF

101   CALL CDEDST(SYSOUT,L,NX1,NX2,AREA,DW,DW1,BCF,HMX,HDS)

      IF(NX1.EQ.NX2.AND.START.LE.TIM*L)THEN
         WRITE(3,1)NX1,TIM*L,('_',K=1,66)
      ELSE IF(NX2.EQ.NPAT.AND.NX1.EQ.1.AND.START.LE.TIM*L)THEN
         WRITE(3,9)TIM*L
         WRITE(SYSOUT,9)TIM*L
      ENDIF

      B1=0.0
      F1=0.0
      W1=0.0
      O1=0.0
      P0=0.0
      DO 103 I=1,NTAX
         B(I)=0.0
         F(I)=0.0
         W(I)=0.0
         O(I)=0             ! DTP Changed this to integer format
         P(I)=0.0
         DO J=1,NPAT                 ! Initialise patch totals for PLTOUT
            PBIOM(J,I)=0.0         ! Total Biomass for plot J, sp. I
            PBASA(J,I)=0.0         ! Total BA for plot J, sp. I
            PLAI(J,I)=0.0          ! Total Leaf Area for plot J, sp. I
            PDENS(J,I)=0           ! Total SPH for plot J, sp. I
c           PPROD(J,I) =0.0         ! Mean Productivity for plot J, sp. I
            TAXAGE(J,I)=0          ! Oldest age of sp. I on plot J
         ENDDO
103   CONTINUE
```

```
      DO 104 M=1,NCL
         N1(M)=0
         NN1(M)=0
         IA1(M)=0
         DO 105 I=1,NTAX
            N(I,M)=0
            NN(I,M)=0
            IA(I,M)=0
105      CONTINUE
104   CONTINUE

      DO 106 I=1,NTAX
         BHMN(I)=HMX(I)
         BHMX(I)=0.0
         HMAX(I)=0.0
         AMX(I)=0.0
         AMN(I)=(L+1)*TIM
106      CONTINUE

      DO 200 J=NX1,NX2
         DO 201 I=1,NTAX
201         Q(I)=W(I)
         DO 202 K=1,MAXIND    ! Should be possible to change this to K=1,NTREE(J)
where NTREE(J) <= MAXIND ???
            T=TAX(J,K)
            IF(T.EQ.0)GOTO 203
            D=DBH(J,K)
            LF=LEA(J,K)                        ! Leaf area
            H=HEIGHT(D,HMX(T),HDS(T))
            IF(HMAX(T).LT.H)HMAX(T)=H
            IF(AMX(T).LT.AGE(J,K))AMX(T)=AGE(J,K)
            IF(AMN(T).GT.AGE(J,K))AMN(T)=AGE(J,K)
            ICL=INT(D/DCWDTH)+1
            IF(ICL.GT.NCL)ICL=NCL
            JCL=INT(H/HCWDTH)+1
            IF(JCL.GT.NCL)JCL=NCL
            KCL=INT(AGE(J,K)/AGWDTH)+1
            IF(KCL.GT.NCL)KCL=NCL
            N(T,ICL)=N(T,ICL)+1                ! Accumulate into species DBH
class
            NN(T,JCL)=NN(T,JCL)+1              ! Accumulate into species height
class
            IA(T,KCL)=IA(T,KCL)+1              ! Accumulate into species age
class
            N1(ICL)=N1(ICL)+1                  ! Accumulate into DBH class
            NN1(JCL)=NN1(JCL)+1                ! Accumulate into height classs
            IA1(KCL)=IA1(KCL)+1                ! Accumulate into age class
            BASA=P4*D*D                        ! Basal area cm2
            BIOM=D*D*H*BCF(T)/1.E3             ! Biomass (converted from kg to
Mg)
            H1=HBC(J,K)
```

```
            IF(H1.GT.BHMX(T))BHMX(T)=H1
            IF(H1.LT.BHMN(T))BHMN(T)=H1

            B(T)=B(T)+BASA                    ! Total BA for this sp.
(cm2)
            B1=B1+BASA                        ! Total BA for all spp.
(cm2)
            W(T)=W(T)+BIOM                    ! Total Biomass for this sp.
(Mg)
            W1=W1+BIOM                        ! Total Biomass for all spp.
(Mg)
            F(T)=F(T)+LF                      ! Total LA for this sp.
(m2)
            F1=F1+LF                          ! Total LA for all spp.
(m2)
            O(T)=O(T)+1                       ! Total Stems of this sp.
(stem)
            O1=O1+1                           ! Total Stems of all spp.
(stem)

            TAXAGE(J,T)=MAX(TAXAGE(J,T),AGE(J,K)) ! Determine oldest tree of sp T
(yr)
            PBIOM(J,T) = PBIOM(J,T)+BIOM      ! Total Biomass for plot J, sp. T
(Mg)
            PBASA(J,T) = PBASA(J,T)+BASA      ! Total BA for plot J, sp. T
(cm2)
            PLAI(J,T)  = PLAI(J,T)+LF         ! Total LA for plot J, sp. T
(m2)
            PDENS(J,T) = PDENS(J,T)+1         ! Total Stems in plot J, sp. T
(stem)

*           BIOM2=BIOM*BIOM                   ! Square the biomass for stats
*           W2(T)=W2(T)+BIOM2                 ! Sum of Biomass^2 for this sp.
*           W12=W12+BIOM2                     ! Sum of Biomass^2 for all spp.

202      CONTINUE

203      DO 204 I=1,NTAX
            P(I)=P(I)+PRO(J,I)       ! Gross wood prodn for this species
            P0=P0+PRO(J,I)           ! Gross wood prodn for all species
                                     ! Q is previous timestep value of live
biomass
            C(J,I)=W(I)-Q(I)         ! C is the live biomass for plot J sp. I (Mg)
204      CONTINUE
200   CONTINUE

* writes all aspects of the stand description for living trees

      IF(START.LE.TIM*L)THEN
c        CALL DISTR(NCL,DCWDTH, ' CM DBH ', NTAX,N,N1)
c        CALL DISTR(NCL,HCWDTH, 'M HEIGHT', NTAX,NN,NN1)
c        CALL DISTR(NCL,AGWDTH, 'YEAR AGE', NTAX,IA,IA1)
```

```
***********************************************************************
* DTP 99/06/24: Changed these for Pingree Park Experiment
          BIOMAS(L,NTAX+1) = 0.0          ! Initialise
          DENSTY(L,NTAX+1) = 0

          DO 300 I=1,NTAX

* prepare data for graph output to FORCLI.out

            LEAFA(L,I) =F(I)/AREA/1.E4     ! Mean stand LAI      (m2/m2)
            DENSTY(L,I)=NINT(O(I)/AREA)   ! Mean stand density (stem/ha)
            BASALA(L,I)=B(I)/AREA/1.E4     ! Mean basal area     (m2/ha)
            BIOMAS(L,I)=W(I)/AREA          ! Mean biomass        (Mg/ha)

* DTP 94/03/14: Following statement calculates mean productivity for species I
* in the current timestep (averaged over the last stand description interval) as
* the difference of [live, W(I), + dead, DW(I), biomass components for species I]
* MINUS [total species biomass at the end of the previous stand description,
P(I)].
* NOTE P(I) = Sum[PRO(J,I) over all J plots] = [C(J,I) from previous stand
* description] = live biomass of species I in plot J.
            PRODY(L,I)=(W(I)+DW(I)-P(I))/AREA/(TIM*LPR) ! Mean prody (Mg/ha/yr)

* write to screen and FORCLI.out
* leaf area,basal area,biomass, density and production for each period

            WRITE(SYSOUT,8)NAM(I),LEAFA(L,I),BASALA(L,I),BIOMAS(L,I),
     +           DENSTY(L,I),PRODY(L,I)

            WRITE(3,8)NAM(I),LEAFA(L,I),BASALA(L,I),BIOMAS(L,I),
     +           DENSTY(L,I),PRODY(L,I)

* write out some output files that can be used as input to SAS

* basal area in basala.out

            WRITE(14,10)L*TIM,NAM(I),BASALA(L,I)

* biomass in biomas.out

            WRITE(15,10)L*TIM,NAM(I),BIOMAS(L,I)

* production in produc.out

            WRITE(16,10)L*TIM,NAM(I),PRODY(L,I)

* DTP 15 July 1993: stems per ha in densty.out

            write(17,12)L*TIM,NAM(I),DENSTY(L,I)

* DTP All the above diagnostic parameters to FOREST.DAT
```

```
* DTP 96/07/23 Also write average tree size in kg (by species)

***********************************************************************
* DTP 99/06/24: Changed these for Pingree Park Experiment
*            IF(DENSTY(L,I).GT.0)THEN
*              AVTREE=1000*BIOMAS(L,I)/DENSTY(L,I)
*            ELSE
*              AVTREE=0.0
*            ENDIF
*            write(18,20)L*TIM,NAM(I),BASALA(L,I),BIOMAS(L,I),
*     >                  PRODY(L,I),DENSTY(L,I),AVTREE

             TOTLAI = TOTLAI + LEAFA(L,I)    ! Total LAI of all species (m2/m2)

300       CONTINUE

* biomass summary for graphical analysis in biomas.grf


***********************************************************************
* DTP 99/06/24: Changed these for Pingree Park Experiment
       write(18,506)L*TIM, (BIOMAS(L,I),I=1,NTAX+1),
     >                     (DENSTY(L,I),I=1,NTAX+1),TOTLAI

 506   FORMAT(I5,'\t',<NTAX+1>(F10.3,'\t'),
     >                <NTAX+1>(I7,'\t'),F6.3)

      ENDIF

C     IF(NX1.EQ.NX2)GOTO 100
      IF((NX1.EQ.NX2).AND.(NPAT.GT.1))GOTO 100  ! DTP 96/10/15 added this fix for
single patch runs
      DO 400 J=1,NPAT
         NUM(J)=0               ! Clear out all dead trees -
         DO 400 I=1,NTAX
            PRO(J,I)=C(J,I)     ! Update productivity values?
400   CONTINUE

* DTP 20 December 1993: Write out stand indices by plot...If SWPLOT is set
* DTP 24 September 1996: Modified this to print out only for years 600 to 1100
*                        of the run. Hence: 800 year runs will produce only 200
*                        years of inventory data, and those simulating climate
*                        change for years 800-900 will produce 500 years of
*                        output bracketing the 100-year transition period.
      IF(SWPLOT.GT.0)THEN
         IF(SWDIST.GT.0)THEN
            IF((L*TIM.GT.600).AND.(L*TIM.LE.1100).AND.
     >         (MOD(L*TIM,LPR).EQ.0))THEN
               CALL PLTOUT(NTAX,NPAT,NAM,PAT,PTCAGE,TAX,DORE,LPR)
            ENDIF
         ELSE ! SWDIST=0 => no disturbances
            IF((L*TIM.LE.1100).AND.(MOD(L*TIM,LPR).EQ.0))THEN
```

```
               CALL PLTOUT(NTAX,NPAT,NAM,PAT,PTCAGE,TAX,DORE,LPR)
            ENDIF
         ENDIF
      ENDIF


* DTP Generate DBH distribution

      IF(SWDBHD.GT.0)THEN
         IF(SWDIST.GT.0)THEN
***********************************************************************
* DTP 99/06/24: Changed these for Pingree Park Experiment
*            IF((L*TIM.GT.600).AND.(L*TIM.LE.1100).AND.
*     >         (MOD(L*TIM,LPR).EQ.0))THEN
*               CALL DBHOUT(NAM,PTCAGE,DORE,LPR,T)
*            ENDIF

            IF(L*TIM.EQ.150) THEN
*            IF((L*TIM.EQ.600).OR.(L*TIM.EQ.1200))THEN
               CALL DBHOUT(NAM,PTCAGE,DORE,LPR,T)
            ENDIF
         ELSE ! SWDIST=0 => no disturbances
            IF((L*TIM.LE.1100).AND.(MOD(L*TIM,LPR).EQ.0))THEN
               CALL DBHOUT(NAM,PTCAGE,DORE,LPR,T)
            ENDIF
         ENDIF
      ENDIF
      RETURN

* format statements:

1     FORMAT(/' DESCRIPTION OF PATCH',I4,' AFTER',I6,' YEARS  ___'
     +        ,'____ Living trees ',66A1/)
2     FORMAT(/' DESCRIPTION OF THE TOTAL STAND AFTER',I6,' YEARS ____'
     +        ,'__ Living trees ',62A1/)
8     FORMAT(1X,A8,X,'LAI',F8.3,X,'BASAL',F8.3,X,'BIOM',F8.3,
     +       X,'DENS',I5,X,'PROD',F8.3)
9     FORMAT(/' DESCRIPTION OF TOTAL STAND AFTER',I6,' YEARS - LIVING
     + TREES')
10    FORMAT(X,I4,X,A8,X,F10.3)
12    FORMAT(X,I4,X,A8,X,I7)

11    FORMAT(X,I4,X,30F7.1)
20    FORMAT(X,I5,X,A8,3(X,F12.3),X,I7,X,F12.3)

      END  ! SUBROUTINE CSTAND

*****************************************************************************

      SUBROUTINE CETBL(J,L,SYSOUT,PTCAGE)
      IMPLICIT NONE
```

```
* CLIMATE and LANDSCAPE version 1990

*DTP 21 October 1998.
*     Changed Model configuration to allow more trees per plot. This has to be
*     fixed in all COMMON blocks. Put COMMONs into compar.h include files so
*     that these can be modified conveniently.

      INCLUDE 'compar.h'     ! global model parameters
      INCLUDE 'comrun.h'     ! settings for this run
      INCLUDE 'comsite.h'    ! site and climate variables
      INCLUDE 'comtax.h'     ! species parameters
      INCLUDE 'comtree.h'    ! tree parameters

* subroutine arguments
      INTEGER SYSOUT, J, L, PTCAGE(MAXPAT)

* function declarations

      REAL    RAND2

* local variables

      INTEGER I,K,NTREES,NSAP
      REAL    TLA,LAI,GSLITE,M4LITE
      REAL    AMDEST(MAXSPE),PFORET(MAXSPE),PFULL(MAXSPE),PMX(MAXSPE),
     %        CO2ALP(MAXSPE),AMDX(MAXSPE)

* computes number of trees and total leaf area on the patch
      NTREES=0
      TLA=0.0
      DO 100 K=1,MAXIND
         IF(TAX(J,K).EQ.0)GOTO 200
         TLA=TLA+LEA(J,K)
         NTREES=K          ! This could be moved outside the loop
100   CONTINUE
* DTP This is probably not totally legal FORTRAN but let's try it....
*      NTREES = K

* computes leaf area index and light at the forest floor

200   LAI=TLA/PAT/1.E4
      GSLITE=EXP(-KCO*LAI)*XGSINS
      M4LITE=EXP(-KCO*LAI)*XM4INS


* plant an appropriate (random) number of saplings of any taxon
* for which light conditions on the forest floor permit growth
* and climate is suitable for establishment.

      DO 300 I=1,NTAX

* apply CO2mx to half-saturation point (ALP)
```

```
         CO2ALP(I)=ALP(I)*CO2MX(I)

* work out P at forest floor and P in full light then use ratio of
* both as a growth multiplier

* deciduous or evergreen
         IF(DORE(I).EQ.0)THEN

            PFORET(I)=(KCO*GSLITE-LCP(I))/(KCO*GSLITE+CO2ALP(I)-LCP(I))
            PFULL(I)=(KCO*XGSINS-LCP(I))/(KCO*XGSINS+CO2ALP(I)-LCP(I))
            PMX(I)=PFORET(I)/PFULL(I)

         ELSE

            PFORET(I)=(KCO*M4LITE-LCP(I))/(KCO*M4LITE+CO2ALP(I)-LCP(I))
            PFULL(I)=(KCO*XM4INS-LCP(I))/(KCO*XM4INS+CO2ALP(I)-LCP(I))
            PMX(I)=PFORET(I)/PFULL(I)

        ENDIF

* amend the EST for climate according to the climate multipliers

         AMDEST(I)=EST(I)*GDDMX(I)*DRMX(I)*TCMX(I)*TWMX(I)*PMX(I)
     %            *TFTMX(I,L)*TWARMX(I)*CO2MX(I)
* DTP The following is a modification to emulate rapid regeneration typical of
* North American boreal stands. It adjusts AMDEST by a random factor between
* 0 and 10, if and only if the patch was just disturbed (i.e., if PTCAGE=1).
* This should allow a very dense stand to regenerate relatively fast).
* It will be interesting to see whether this favours particular species (like
* jack pine) in the early stages of succession.


* if first year set patch age to 1
* TLS in former version PTCAGE was only assigned later in LTVXT but is needed
* here for determining rapid regen in year 1

            IF(L.EQ.1)PTCAGE(J)=1

c        IF(PTCAGE(J).LT.2) AMDEST(I)=AMDEST(I)*RAND()*10

*TLS amendment to favor rapid post-fire establishment of pioneer species
*5 is black spruce, 6 is jack pine and 9 is aspen

         IF(PTCAGE(J).LT.2)THEN
         IF(I.EQ.5.OR.I.EQ.6.OR.I.EQ.9)AMDEST(I)=AMDEST(I)*50
         ENDIF
C     WRITE(3,10)I,AMDEST(I),EST(I),gslite,m4lite,PFORET(I),
C    %      PFULL(I),PMX(I),tftmx(I,L),twarmx(I),xgsins,xm4ins
C 10  FORMAT(1X,'CETBL ',I2,2X,F6.2,2X,F6.2,2X,F6.2,2X,F6.2,2X,
C    +        F6.2,2X,F6.2,2X,F6.2,1x,f6.2,1x,f6.2,1x,f6.2,1x,f6.2)
```

```
* TLS amend growth based on environmental conditions. If no growth in given year,
* there will also be no regeneration. Former version used GSC=0 but GSC is
* the assigned species growth parameter which is never zero.


          AMDGSC(I)=GSC(I)*GDDMX(I)*DRMX(I)*TCMX(I)
     %                      *TFTMX(I,L)*CO2MX(I)

        IF(AMDGSC(I).EQ.0.0)GOTO 300
           AMDX(I)=AMDEST(I)*PAT*TIM !TLS removed from argument list to debug
        CALL PRAND(AMDX(I),NSAP)      !CALL PRAND(AMDEST(I)*PAT*TIM,NSAP)
        IF(NSAP.EQ.0)GOTO 300

        DO 301 K=NTREES+1,NTREES+NSAP
           IF(K.GE.MAXIND)THEN  ! These mods added by DTP 92/04/30.
C             write (sysout,1002) K,NTREES,NSAP(I),MAXIND
1002          FORMAT (' too many trees in ETBL',
     +        '  K=',I5,' NTREES=',I5,' NSAP(I)=',I5,' MAXIND=',I5)
C             PAUSE
              STOP 'too many trees in ETBL'
           ENDIF
           TAX(J,K)=I
           DBH(J,K)=DBH0+RAND2()*INC(J,I)
           HBC(J,K)=0.0
           AGE(J,K)=0
           LEA(J,K)=LAC(I)*(DBH(J,K)**2)
301        CONTINUE
        NTREES=NTREES+NSAP
300     CONTINUE
      RETURN

      END  ! SUBROUTINE CETBL
```