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A PHYSIOLOGICAL EXPLANATION FOR VEGETATION ECOTONES IN EASTERN NORTH AMERICA

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HYDROLOGY AND WATER RESOURCE SYSTEMS

Report Number 323

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Abstract

Prediction of the vegetative cover of land surfaces as climatic conditions change is an important aspect of general circulation models that has not been adequately explored. In this study, a model is developed for the purpose of predicting the location of two major vegetation ecotones in eastern North America based on the interaction of plant physiological characteristics, climate, and edaphic influences.

The model represents the relative competitive ability of different vegetation types by their annual net primary productivity. At any given location, the vegetation type with the highest productivity is predicted to be the dominant type. Ecotones are located where competitive dominance shifts from one vegetation type to another. Productivity is computed as a function of annual evapotranspiration, which is a function of the length of the growing season, photosynthetic capacity, potential evapotranspiration, and soil moisture availability, among other things.

When considering the boreal/deciduous forest ecotone, it is found that inherent physiological differences between conifers and deciduous trees lead to differences in productivity which are related primarily to temperature. The model predicts deciduous dominance to a latitude slightly north of the observed ecotone location. However, an absolute physiological limit in the form of low temperature tolerance is apparently preventing the deciduous forest formation from further northward migration.

It was necessary to include soil characteristics when considering the deciduous/southern pine ecotone. Water limitations apparently play a role in the determination of this boundary, although the model results indicate that an additional limiting factor is also operating at this ecotone. It is suggested that nutritional limitations may be present as a result of the soil characteristics of the region, and that this may contribute to the dominance of pine in the south.

Acknowledgements

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Notation

Symbol	Definition	Dimensions
A	carbon assimilation	(mg CO_2 m^{-2}[land] day^{-1})
a	coefficient in interception equation	(cm)
B	fitting parameter for Mualem/Milly model	(–)
b	coefficient in interception equation	(–)
C	photosynthetic capacity	(–)
CC	Julian day of initial color change	(days)
c	pore disconnectedness index	(–)
D	fitting parameter for Mualem/Milly model	(–)
DD	degree days	(–)
d	diffusivity index	(–)
E	evaporation effectiveness	(–)
E_P	potential evapotranspiration	(cm day^{-1})
E_T	actual evapotranspiration	(cm day^{-1})
$\overline{E}_{T_{ds}}$	average dormant season evaporation	(cm day^{-1})
$\overline{E}_{T_{gs}}$	average growing season evapotranspiration	(cm day^{-1})
e	days elapsed from budbreak	(days)
e_s	saturated vapor pressure at mean daily air temperature	(Pa)
F	Hamon correction factor	(–)
f	regression coefficient for Rawls model	(–)
G	fitting parameter for Mualem/Milly model	(–)
g	regression coefficient for Rawls model	(–)
H	water content of soil column	(cm)
h	total storm depth	(cm)

Notation

(continued)

h_e	effective storm depth	(cm)
I	interception	(cm)
i	regression coefficient for Rawls model	(–)
j	regression coefficient for Rawls model	(–)
K(1)	saturated hydraulic conductivity	(cm hr^{-1})
k	crop coefficient	(–)
k(1)	saturated effective intrinsic permeability	(cm^2)
L	leaf area index	(m^2[leaf] m^{-2}[land])
M	% total forest cover represented by any species	(–)
m	pore size distribution index	(–)
m_{tb}	average time between storms	(days)
m_{tr}	average storm duration	(days)
m_τ	average length of the rainy season	(days)
NPP	net primary productivity	(g dry weight m^{-2}[land] yr^{-1})
n	porosity	(cm^3 voids cm^{-3} soil)
n_e	effective porosity	(–)
n_s	average number of storms in a season	(–)
n_{se}	effective number of storms in a season	(–)
P_A	average annual precipitation	(cm)
P_e	effective annual precipitation	(cm)
$\overline{P}_{ds}$	average dormant season precipitation	(cm day^{-1})
$\overline{P}_{gs}$	average growing season precipitation	(cm day^{-1})
p	percentage of leaves emerged	(–)

Notation

(continued)

Q	fitting parameter for Mualem/Milly model	(–)
R	dry air gas constant	($J\ kg^{-1}\ K^{-1}$)
s	soil moisture concentration	(–)
s_e	effective soil moisture concentration	(–)
s_0	time and space average soil moisture concentration	(–)
T	absolute mean daily surface air temperature	(K)
T_a	surface air temperature	(°C)
t	seasonal time	(days)
u	regression coefficient for Rawls model	(–)
V	fitting parameter for Mualem/Milly model	(–)
W	soil moisture factor	(–)
x	Hamon constant	($m^3\ cm\ day\ kg^{-1}\ hr^{-2}$)
y	possible amount of sunshine	(days)
z_r	soil depth	(cm)
α	water use efficiency of production	(g dry weight $g^{-1}\ H_2O$)
β	reciprocal of time between storms	($days^{-1}$)
γ_w	specific weight of water	($N\ cm^{-1}$)
η	water use efficiency of assimilation	(mg $CO_2\ g^{-1}\ H_2O$)
ψ	soil moisture potential	(bars, cm or Pa)
$\psi(1)$	saturated soil moisture potential	(cm)
κ	parameter of gamma distribution	(–)
λ	parameter of gamma distribution	(cm^{-1})
μ_w	dynamic viscosity of water	(N–s cm^{-2})

Notation

(continued)

θ	volumetric soil moisture content	(cm^3 H_2O cm^{-3} soil)
θ_r	residual soil moisture content	(cm^3 H_2O cm^{-3} soil)
θ_u	proportion of soil occupied by water after rewetting	(cm^3 H_2O cm^{-3} soil)
ρ_S	saturated vapor density at mean daily air temperature	(kg m^{-3})
σ_w	surface tension of water	(N cm^{-1})
τ	growing season length	(days)
ϕ	latitude	(degrees)
ϕ_e	exfiltration diffusivity	(-)
Φ	pore shape parameter	(-)
$\Gamma(x)$	gamma function	(-)
$\Gamma(\alpha, x)$	incomplete gamma function	(-)
$\theta_d(\psi)$	main drying function, Milly/Mualem model	(-)
$\theta_w(\psi)$	main wetting function, Milly/Mualem model	(-)

List of Species

Scientific Name	Common Name
Abies balsamea (L.) Mill.	Balsam fir
Abies fraseri (Pursh) Poir.	Fraser fir
Acer rubrum L.	Red maple
Acer saccharum Marsh.	Sugar maple
Aesculus spp.	Horse–chestnut
Alnus rugosa (Du Roi) K. Koch.	Speckled alder
Betula lutea Michx. f.	Yellow birch
Betula nigra L.	River birch
Betula papyrifera Marsh.	Paper birch, white birch
Carya cordiformis (Wangenh.) K. Koch	Bitternut hickory
Carya ovata (Mill.) K. Koch	Shagbark hickory
Fagus grandifolia Ehrh.	American beech
Fraxinus americana L.	White ash
Fraxinus nigra Marsh.	Black ash
Fraxinus pennsylvanica Marsh.	Green ash
Juglans cinerea L.	Butternut
Juglans nigra L.	Black walnut
Larix decidua Mill.	European larch
Larix laricina (Du Roi) K. Koch	Tamarack, Eastern larch
Liriodendron tulipifera L.	Yellow poplar, Tuliptree
Nyssa sylvatica Marsh.	Black tupelo
Picea abies (L.) Karst.	Norway spruce
Picea glauca (Moench) Voss	White spruce
Picea mariana (Mill.) BSP	Black spruce
Picea rubens Sarg.	Red spruce
Pinus banksiana Lamb.	Jack pine
Pinus cembra	Stone pine, Siberian pine, Arolla pine
Pinus contorta Dougl. ex Loud.	Lodgepole pine
Pinus echinata Mill.	Shortleaf pine
Pinus elliotti Engelm.	Slash pine
Pinus palustris Mill.	Longleaf pine
Pinus ponderosa Dougl. ex Laws.	Ponderosa pine
Pinus resinosa Ait.	Red pine
Pinus rigida Mill.	Pitch pine
Pinus strobus L.	Eastern white pine
Pinus sylvestris L.	Scotch pine
Pinus taeda L.	Loblolly pine
Platanus occidentalis L.	Sycamore
Populus balsamifera L.	Balsam poplar
Populus deltoides Bartr. ex Marsh.	Eastern cottonwood
Populus grandidentata Michx.	Bigtooth aspen
Populus tremuloides Michx.	Trembling aspen, Quaking aspen
Prunus serotina Ehrh.	Black cherry
Quercus alba L.	White oak
Quercus macrocarpa Michx.	Bur oak
Quercus prinus L.	Chestnut oak
Quercus rubra L.	Northern red oak, red oak

List of Species
(continued)

Scientific Name	Common Name
Quercus velutina Lam.	Black oak
Salix nigra Marsh.	Black willow
Taxodium distichum (L.) Rich.	Baldcypress
Thuja occidentalis L.	Northern white–cedar
Tilia americana L.	American basswood
Tsuga canadensis (L.) Carr.	Eastern hemlock
Ulmus americana L.	American elm

Chapter 1

Introduction

Until very recently, the existence of globally interconnected biological and physical systems was barely acknowledged, much less understood. However, as the effects of human interference with these systems are becoming apparent, a major effort has been mounted to improve our knowledge and understanding of them. The planet earth has been compared to a living organism (Lovelock, 1979) whose health is regulated by the interaction of biotic and abiotic cycles and processes. We are starting to understand that human activities are having a profound impact on these systems, and, as world population continues to grow, these impacts can be expected to intensify. It is therefore of critical importance that we learn as much as we can about the nature of these systems and how they may be expected to behave in the future.

The global climate system is one of the most important systems in terms of its effect upon the biosphere as well as other physical cycles. A number of human activities, including the burning of fossil fuels and deforestation leading to an increase in greenhouse gases, and chlorofluorocarbon production causing the destruction of stratospheric ozone, are likely to create significant changes in global climate in both the short and long term. Since our lives are dependent on climate due to its effect on food production, water supply, and heating, among other things, it is important for us to increase our understanding of this system and begin to attempt to predict what effect our activities are likely to have on it.

The development of large scale numerical models of coupled atmospheric, ocean and land surface dynamics is seen as a primary mechanism for both increasing our understanding of the global climate system and predicting what changes are likely in the future. Characterization of the dynamic behaviour of landsurface processes, including vegetation cover, is essential if these models are to accurately mimic the real systems. One important parameter in these interactions is the type of vegetation at any given location on the planet. Different types of vegetation have very different heat and moisture flux characteristics, and will thereby have different inputs into the climatic system. The current vegetative cover of the globe has been well mapped and thus the initial conditions for these models can be easily specified. However, the response of various vegetation types to changes in climate is very poorly understood and is of critical importance to these models. For long–range predictions of climatic change, the models should include an interactive vegetation component such that global vegetation distributions shift as climate changes.

In studying the response of vegetation to climate, it is helpful to look at the transitions from one vegetation type to another. These are known as ecotones. Because they represent marginal conditions, ecotones will be sensitive to changing climate, and predicting their location is an important test of general circulation models. Existing knowledge of these transitions is primarily in the form of empirical correlations of primary vegetation formations with variables such as temperature, precipitation, latitude, and so on (see Chapter 2 for a detailed review). While these relationships may provide some clues to the underlying physical mechanisms, there is no guarantee that they will hold as climatic conditions change.

At the other extreme are very complex models which "grow" individual plants, and chart the changes in vegetation systems over many generations of plants (Chapter 2). Although these models have been quite successful in simulating current conditions, and could undoubtedly aid in the prediction of future distributions as well, they have several limitations. Their greatest shortcoming is the use of a large number of parameters, which means that either extensive field research must be done to collect the necessary data or parameters must be estimated, which then reduces their reliability. In addition, a model which grows trees may not be adequate to predict the transition from forest to grassland. Incorporation of all the different plant life forms into this type of model would produce extremely complex models, which can often obscure the essential physical processes which underlie them.

The approach that we have taken is to strike a middle ground between these extremes. We have developed a model which incorporates the essential aspects of plant physiology that determine a plant's response to its environment, yet is simple enough to require a minimum number of parameters which must be measured or estimated. Due to the scope of this project, we have limited the study to the two major vegetation ecotones in eastern North America. These consist of the transition from boreal forest to deciduous forest in the north, and the transition from deciduous forest to pine forest in the south (Figure 1, redrawn from Eyre, 1968).

There are several key assumptions which underlie the creation of this type of model. The first assumption is that the distribution of vegetation on a global scale is indeed primarily controlled by climate or by a combination of climatic and other quantifiable factors. This premise seems to be generally agreed upon by plant ecologists, and examples abound in the literature (Chapter 2).

The second major assumption is that relationships between plant types are competitive. This invokes a "survival of the fittest" argument in that the model assumes that the plant which can fix the most carbon in a given environment will produce the most biomass. This will improve its capacity to grow and reproduce, eventually enabling it to dominate in that environment. It is important to note that the vegetation types under consideration here are the climax vegetation types for each formation, reasoning that early successional vegetation will be transitory and not critical in determining ecotone locations.

A final assumption in using this model to predict the future location of

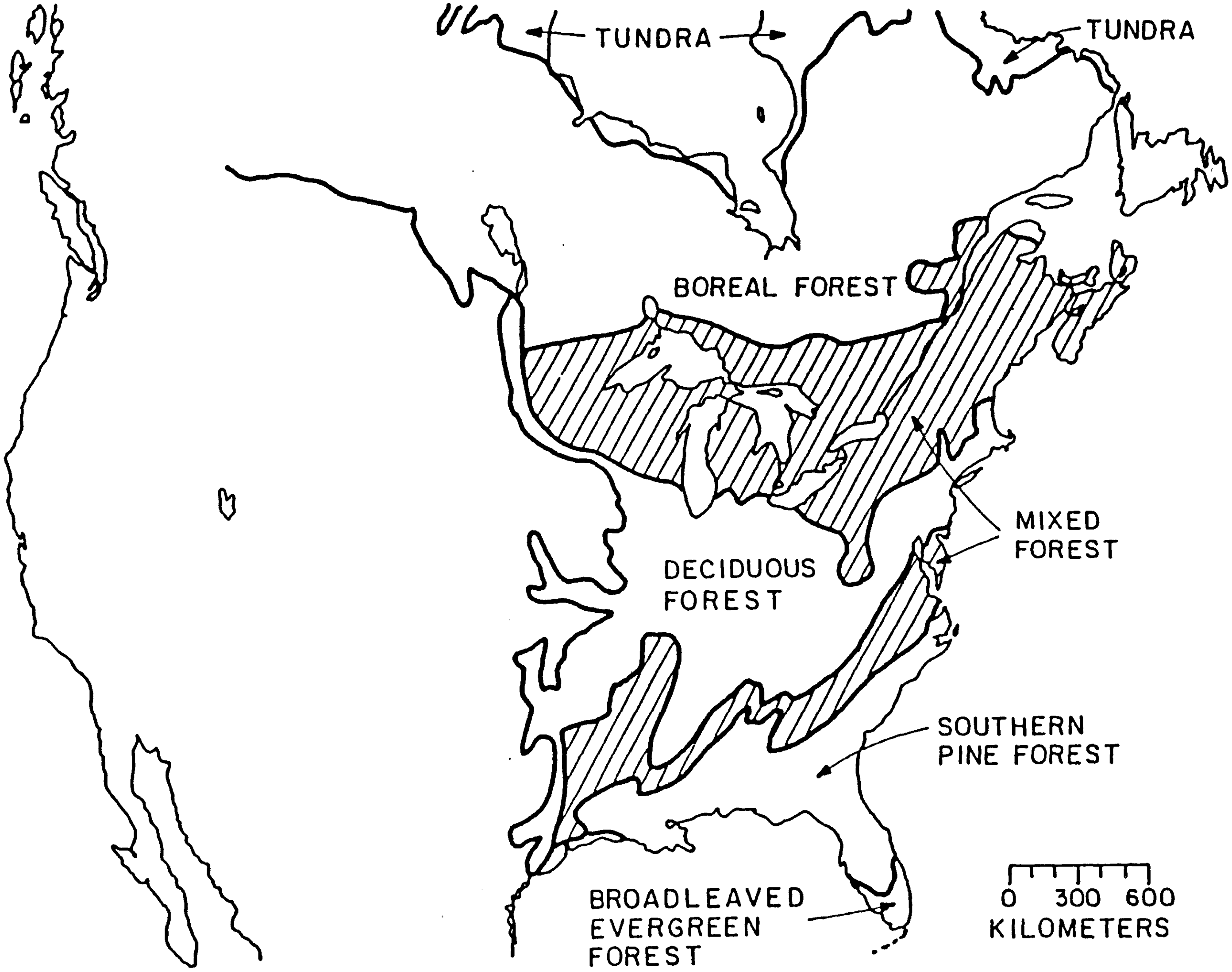

Figure 1: Forest formations of eastern North America (map from Little (1971), boundaries from Eyre (1968)).

vegetation ecotones as climate changes involves the question of time scales. The model is an equilibrium–type model in that we assume that climatic change will be operating over a shorter time scale than that necessary for a given type of vegetation to adapt to changing conditions, but that it will be slow enough to allow plants to migrate as conditions change. The latter part of this assumption, that of migrating vegetation being able to keep pace with changing climate, is perhaps the weakest assumption of the model. Current projections show increases of global temperature of 1 to 5 degrees within 100 years, whereas the life span of a single tree is at least that, and migration rates may only be a few meters per year (Huntley & Birks, 1983). This is addressed in more detail in Chapter 9.

We have developed a model which uses net primary productivity as a surrogate for competitive ability. Applying it, we find that consideration of temperature limitations in terms of freezing stress and growing season is adequate to predict the observed location of the deciduous forest/boreal forest ecotone. We found it necessary to add moisture limitations and soil characteristics when characterizing the southern pine/deciduous forest ecotone. Even including these factors in our analysis we did not come up with a definitive explanation for this boundary, and we hypothesize that nutrient limitations may play a role as well.

Chapter 2

Historical Review of Climate/Vegetation Relationships

The relationship between the distribution of vegetation and climate has been recognized by researchers from at least the beginning of this century (see Tosi, 1964 for a review of the early literature). Much of the research done in this area has focused on smaller regions, often considering only one or two ecotones (cf. Shreve, 1914; Hellmers, 1962; Waring and Major, 1964). There are, however, a few major contributions which attempt to classify all of the vegetation types of the world into specific climatic categories. These works are empirical in that they correlate the location of vegetation types with climatic parameters without specifically considering the causal relationships that may exist. However, the relationships which are illustrated by these classification schemes can aid in the development of causal models by indicating which climatic factors are important and which can be neglected when considering specific ecotones.

Initially, simple parameters such as temperature and precipitation were the primary factors considered. Holdridge (1947) used mean annual precipitation and "biotemperature", defined as the sum of monthly means above 0 °C divided by 12, as the climatic parameters which together defined limits for all possible vegetation types (Figure 2). It is difficult to compare his work with other models due to the differences in terminology he uses to describe vegetation types, however, his work remains as one of the original contributions in this field.

Dansereau (1957) related the climatic types of Kõppen modified by Trewartha (Espenshade and Morrison, 1978) to the formation classes of Schimper and von Faber (1935 cited by Dansereau, 1957). The Koppen classification of climate uses annual moisture, seasonality of moisture, and the temperature of the coldest and warmest months to distinguish climatic types. Tosi (1964) elaborated on the Holdridge (1947)

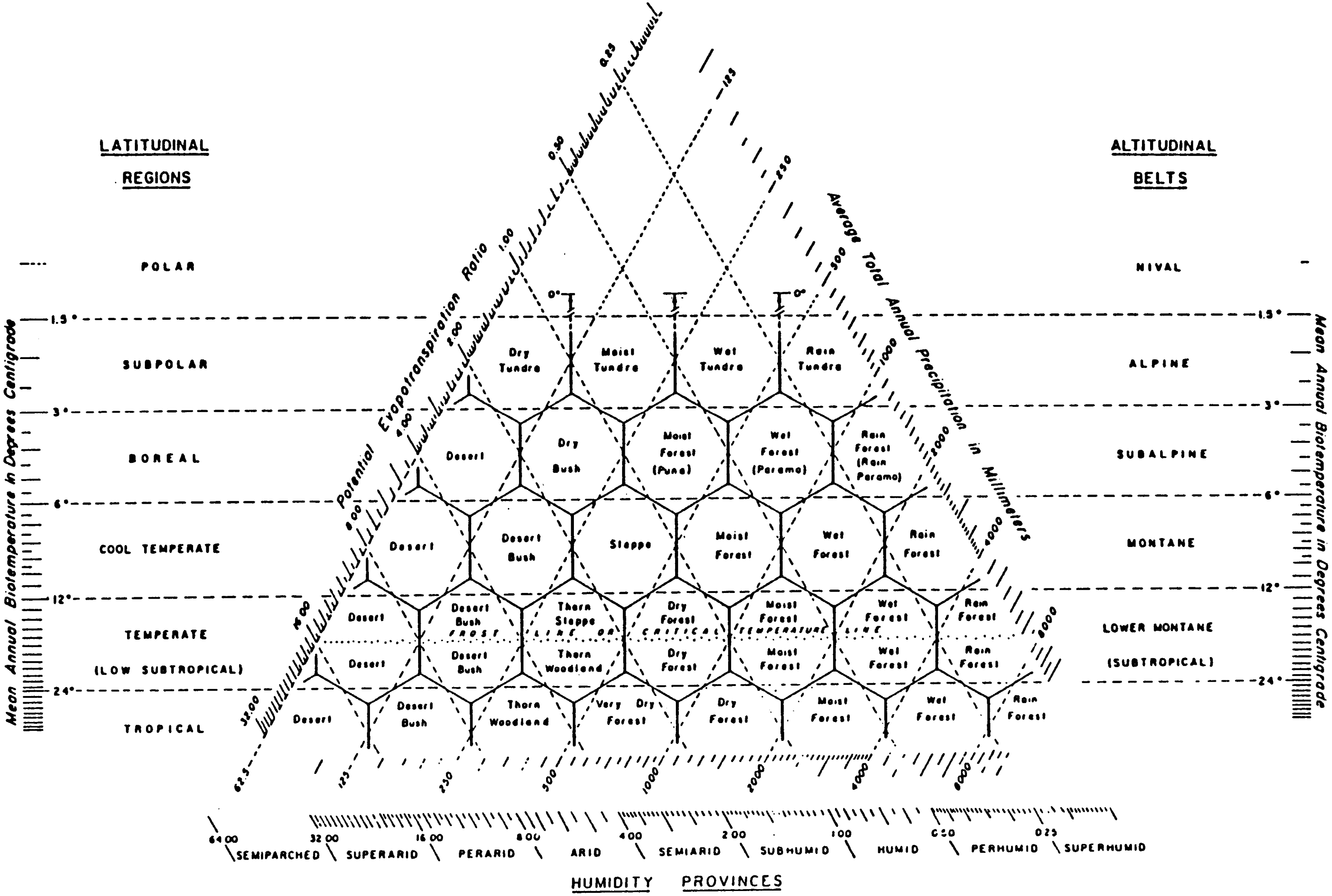

Figure 2: Holdridge diagram for classifying world plant formations (Holdridge, 1947).

model, encouraging its use as a predictive tool. Whittaker (1975) plots global vegetation types against mean annual temperature and precipitation.

Thornthwaite (1948) introduced potential evapotranspiration as an important consideration in climatic classification and defined a moisture index which related potential evapotranspiration to precipitation. Plant geographers recognized the importance of this concept in representing the moisture regime that plants are subject to. Mather and Yoshioka (1968) used Thornthwaite's (1948) moisture index and potential evapotranspiration as axes for a plot of all United States vegetation types and found that almost all of the plotted vegetation types were located in specific, non–overlapping areas of the graph. This permitted them to specify limiting values of these indices for each vegetation type. Szafer (1975) provides an excellent review of temperature, moisture, light and atmospheric conditions as contributing factors in plant distributions but does not propose any overall classification scheme. Yim and Kira (1975) related warmth and coldness indices to vegetation distributions in Japan. Wolfe (1979) studied the humid climates of Asia and found several significant temperature relationships. One interesting discovery was the apparent need for a 20 °C mean annual temperature range for broad leaved deciduous trees to survive, which may exclude them from tropical mountains where other conditions are favorable.

Box (1981) was the first to turn this type of correlation into a predictive model. He used eight variables to define climatic conditions, including temperature, precipitation, and seasonality indicators. These were correlated with 41 different plant life forms, with the upper and lower limits of each climatic variable being defined for each plant life form. These limits were combined with a hierarchical system that determined the dominant life form should two overlap, and a model was developed that would predict the expected vegetation type (life form) for any given climate. The model is circular in that existing vegetation types were used to define the limits that were then used to test the model by predicting existing vegetation types. Sowell (1985) constructed a discriminant model using mean monthly temperatures, precipitation, and latitude to classify and predict vegetation types for the United States.

A second type of model which "grows" individual trees in a stand and incorporates competitive interactions as well as climatic constraints has been developed more recently, with the advent of computers and a sizable data base for model parameterization. The first model of this type , JABOWA, simulates the population dynamics of a mixed species, mixed age northern hardwood forest (Botkin et al., 1972). Shugart and West (1977) modified JABOWA for use in an Appalachian deciduous forest to predict succession and the impacts of chestnut blight. Phipps (1979) used a similar approach to develop SWAMP, a model which simulates southern wetlands forests.

Davis and Botkin (1985) modified JABOWA to simulate the effects of rapid temperature change on cool–temperate forests such as the northern hardwoods of New England. Solomon (1986) used additional modifications to simulate deciduous and boreal forest changes caused by climatic warming due to increasing atmospheric carbon dioxide. Pastor and Post (1986, 1988) simulated the effects on northern forests of climatic changes with an emphasis on soil moisture and nutrient dynamics.

While these models have successfully simulated both past and present vegetation distributions, they have some drawbacks. There are a great number of parameters which must be measured or estimated to run the models. Despite the physiological orientation of the models, many of the parameters used in them are empirical in nature. For example, in the Pastor and Post model (1986), minimum soil moisture requirements in the model are derived from the current range of each species. Finally, these models have been specifically developed for forests and are currently inadequate for predicting other vegetation types.

The third type of possible model consists of one which incorporates physical processes and yet retains as much simplicity as possible. Very few of these models currently exist for predicting vegetation distributions. Eagleson and Segarra (1985) modelled savannah vegetation as a tree–grass system where the vegetation competes for water and solar energy. Although this model considers only two possible vegetation types, it illustrates the simple but physically based approach we wish to use. Woodward (1987) has used the physiological effects of extreme minimum temperatures combined with annual water balance considerations to simulate the location of global vegetation types. Although the model is somewhat physiologically based, no consideration is given to competitive interactions.

Chapter 3

The Major Vegetation Formations of Eastern North America

As stated previously, this analysis is restricted to the two primary ecotones in eastern North America. These ecotones consist of the boreal forest–deciduous forest ecotone in the north and the deciduous forest–southern pine forest ecotone in the south (Figure 1). This section describes each of the three formations in detail.

Formations are physiognomic classifications in that they are based on the dominant growth form of the vegetation with some consideration given to environmental conditions (Whittaker, 1975). There are many references available which delineate the boundaries of the various formations; all of them are quite similar. We have chosen to use Eyre (1968) as our source primarily because the distribution maps are continental in scale rather than stopping at national boundaries as many other sources do. The boundaries shown by Eyre are consistent with those in other sources (Dice, 1943; Braun, 1950; Haden–Guest et al., 1956; Rowe, 1959; Kuchler, 1964; Rowe, 1972; Preston, 1976; Eyre, 1980; Ritchie, 1987; Barbour and Billings, 1988). Table 1 provides a comparison of the terminology used by various authors with that used in this text.

A representative species for each formation has been selected for the purpose of parameter estimation, and this species is described for each formation. Criteria for the selection of a representative species included abundance and dominance, as well as a range that coincided with the boundaries of the formation in question.

3.1 Boreal Forest

Boreal forest, or taiga, is the northermost vegetation type considered here. It

Table 1

Comparison of Formation and Ecotone Terminology

Reference	Term	Boreal Forest	Ecotone	Deciduous Forest	Ecotone	Southern Pine Forest
Dice, 1943	biotic province	Hudsonian	Canadian	Carolinian		Austroriparian
Gleason & Cronquist, 1964	floristic province	Northern Conifer Province	Eastern Deciduous Forest Province			Coastal Plain Province
Eyre, 1968	plant formation	boreal coniferous forest	lake forest	deciduous summer forest	mixed forest	southern pine forest
Whittaker, 1975	formation or biome	taiga		temperate deciduous forest		temperate evergreen forest
Box, 1981	plant form	boreal/montane needle–trees		summergreen broad–leaved trees: typical temperate mesophyllous		temperate needle–leaved trees: heliophilic large–needled
Walter, 1985	zonobiome	VIII cold–temperate boreal coniferous		VI nemoral broadleaf deciduous		V temperate evergreen forest
	zono–ecotone		VIII–VI		V–VI	

stretches from Alaska in the west to Newfoundland in the east, and is bounded in the north by tundra vegetation. In the south, it borders on several different ecotones, of which the eastern deciduous forest is the only one of interest here. The transition from boreal forest to deciduous forest consists of a broad band of mixed forest, containing varying proportions of species from both ecotones (see Figure 1).

The boreal forest is predominantly coniferous, consisting of species of spruce (*Picea*), pine (*Pinus*), fir (*Abies*) and larch (*Larix*) There are also two hardwood genera, poplar (*Populus*) and birch (*Betula*), which are often important successional species after disturbances (Ritchie, 1987). The most abundant species throughout the boreal forest are white spruce (*Picea glauca* (Moench) Voss) and black spruce (*Picea mariana* (Mill.) BSP) (Elliott–Fisk, 1988).

There are several important physiological characteristics of the boreal conifers which may contribute to their dominance in the extreme northern climates in which they are found. The boreal conifers are needle leaved and, with the exception of the genus *Larix*, are evergreen. This confers a possible competitive advantage by allowing photosynthesis over a longer time period than that of deciduous trees (Chabot and Hicks, 1982; Oechel and Lawrence, 1985). However, due to the extreme climate characteristic of the boreal regions, the needles must also be capable of surviving extremely low temperature conditions, which prevent year–round photosynthesis and may entail additional resources diverted to cold resistance mechanisms (Neilson et al.,1972; Oquist, 1986; Woodward, 1987). The needles of the boreal conifers are typically dark green and clustered, which may enhance photosynthesis at low temperatures by increasing the temperature of the needles up to 20 °C above ambient air temperatures (Hadley and Smith, 1987).

Conifers have lower photosynthetic rates (measured in amounts of carbon fixed per unit of biomass per unit of time) than deciduous hardwoods (Mooney, 1972; Oechel and Lawrence, 1985). They also have lower transpiration rates, due to smaller vessels in the conducting system and greater minimum stomatal resistances than deciduous trees (Larcher, 1983). These characteristics, coupled with the low net annual radiation and cold temperatures of the boreal regions, leads to lower net primary productivity values for the boreal forest than for any other forest formation (Whittaker, 1975).

The boreal conifers utilize a specific method of freezing resistance known as extracellular or extraorgan freezing (Sakai, 1979), which enables them to withstand the extremely cold winter temperatures which are encountered throughout their range. The hardwoods which are found in the boreal regions also exhibit this type of freezing resistance. This will be discussed in greater detail in Chapter 6.

Finally, there are some miscellaneous characteristics that are not considered in our model but which are sometimes cited as adaptations that improve the conifers' competitive ability in the northern climates in which they are found. The conical shape of the boreal conifers as well as the needle–shaped leaf of conifers in general have been mentioned as an ideal adaptation to minimize snow loading in areas of high winter snowfall (Chabot and Hicks, 1982). Additionally, the evergreen habit reduces annual nutrient demands, which may be an advantage in areas where cold temperatures prevent rapid decomposition of litter, thereby leading to soils which are acidic, high in organic matter and low in available nutrients (Monk, 1966; Larsen, 1980; Chabot and Hicks, 1982).

Several hypotheses have been submitted to explain the existence of the northern tree line where boreal forest gives way to tundra vegetation. All of these explanations are linked to temperature constraints. Gleason and Cronquist (1964) state that at least 8 weeks with average temperatures greater than 10 °C are necessary for trees to exist. Bryson (1966) found that the boreal/tundra ecotone corresponded closely to the average summer position of the arctic front which separates the arctic and polar air masses. Hare and Ritchie (1972) found that the treeline correlates well with specific values of net radiation, potential evapotranspiration, and length of the "thaw season". Larsen (1980) found that the ecotone corresponds to the July mean temperature isotherm of 13 °C, and Rouse (1984) compares it with the southern limit of continuous permafrost. The physiological explanation most often cited for the apparent temperature limitation on the existence of the tree growth form is that limited radiation and low temperatures do not allow production and maintenance of biomass in sufficient quantities to support forest vegetation (Larsen, 1980). Similar temperature related factors are thought to influence the location of the boreal–deciduous forest ecotone. These will be discussed in Chapter 6.

Due to its prevalence througout the boreal forest, black spruce (*Picea mariana*) has been selected as the representative species for the boreal forest. Its range includes all of the boreal forest formation and most of the mixed transition region. According to Fowells (1965), it is one of the most abundant conifers in northern North America. It is a fairly small tree, generally 9 to 12 meters high although at the northern limit of its range it may assume a prostrate or shrubby habit due to environmental extremes (Harlow et al., 1979). Black spruce needles are 0.6 to 1.2 centimeters long and 4–sided, with stomata on all surfaces (Preston, 1976) and are persistent for 15 years or more (Hom and Oechel, 1983). The root system is shallow and spreading, especially on the permafrost which occurs over a great deal of its range (Oechel and Lawrence, 1985). Reproductive maturity is reached as early as 10 years of age, and trees may live to be 250 years old. Black spruce is classed as relatively shade–tolerant, although it develops better in the open. Cones are persistent and semi–serotinous (i.e., cones remain partially closed until the heat of a fire opens them), releasing viable seed both at maturity and after fires (Fowells, 1965; Harlow et al., 1979; Hom and Oechel, 1983).

3.2 Eastern Deciduous Forest

The eastern deciduous forest formation occupies most of the United States east of the Mississippi River. The species composition varies widely from north to south, with diversity and number of dominant species typically increasing towards the south Whittaker, 1975). The dominant tree species are generally deciduous, although conifers are interspersed throughout and are especially prevalent in the mixed zones at the northern and southern limits of the formation (Braun, 1950; Greller, 1988).

Characteristics of the deciduous trees which distinguish them from conifers are numerous. As their name implies, the leaves of deciduous trees are broad and seasonally deciduous, appearing in the spring and falling off in the autumn. Deciduous trees have generally higher photosynthetic rates compared with conifers (Hicks and Chabot, 1985). They also have higher transpiration rates due to larger conducting vessels and lower minimum stomatal resistances (Mooney, 1972; Larcher, 1983). Large conducting vessels also have a drawback in that freezing temperatures can cause cavitation, which breaks the water column, thus destroying the capacity of that vessel to conduct water (Zimmerman and Brown, 1971).

The freezing resistance method of the deciduous hardwoods, as well as some of the coniferous species which co–exist with them, is known as deep supercooling or undercooling (George et al., 1974). This mechanism will be discussed in more detail in Chapter 6.

Northern red oak (*Quercus rubra* L.) is a common, widely distributed tree with a range that coincides with the deciduous forest formation and mixed transition regions, therefore it was selected as the representative species for the deciduous forest formation. This oak is typically 18 to 27 meters high with a deep, spreading root system. Reproductive maturity is reached between 25 and 50 years of age, and trees may reach an age of 300 years. Shade tolerance is intermediate (Fowells, 1965; Harlow et al., 1979).

3.3 Southern Pine Forest

The southern pine formation lies primarily along the southeastern coastal plain, extending almost to the southern tip of Florida in the south, and grading into the deciduous forest type in the north. Often mixed with oak (*Quercus spp.*) in varying quantities, the dominant species are longleaf pine (*Pinus palustris* Mill.), shortleaf pine (*Pinus echinata* Mill.), loblolly pine (*Pinus taeda* L.) and slash pine (*Pinus elliottii* Engelm.).

Many of the characteristics of the pines are similar to the boreal conifers: evergreen, needle leaves; low photosynthesis and transpiration rates. However, their cold resistance mechanisms are extremely different, the southern pines being quite sensitive to cold temperatures due in part to their indeterminate growth form (Oohata and Sakai, 1982). This type of growth form entails the production of several flushes of growth each year which do not appear to be seasonally regulated, as opposed to those trees with determinate growth forms in which a set number of growth flushes occur each season, predetermined by buds which were formed in a previous growing season (Zimmerman and Brown, 1971). The indeterminate growth form may provide a competitive advantage in areas where winter temperatures are not limiting as it allows for year–round growth. It is a disadvantage where temperatures drop below a certain critical minimum with any regularity, because some degree of growth cessation is apparently a prerequisite for cold acclimation (Perry, 1971a).

The soils of the southern pine region are typically sandy, which tends to affect the water balance of the soils as well as their nutrient status. This characteristic may help to explain the dominance of the conifers in this region.

Near the southern tip of Florida, the southern pine formation gives way to broadleaved evergreen forest (Figure 1). This ecotone is also thought to be a result of temperature limitations (Woodward, 1987). Broad–leaved evergreens retain their leaves year–round, however, unlike conifers their leaves are typically very susceptible to cold temperatures. The ecotone in Florida is roughly coincident with the 0 °C average annual minimum temperature isotherm (National Arboretum, 1960; Eyre, 1968), indicating that sensitivity to freezing may be affecting the competitive ability of broad–leaved evergreens north of this boundary (Larcher and Bauer, 1981; Sakai and Larcher, 1987; Woodward, 1987).

Described by Harlow, et al. (1979) as one of the most distinctive and important of the southern conifers, longleaf pine (*Pinus palustris*) was chosen as the representative species for the southern pine formation. Its range coincides almost exactly with that of the formation, extending somewhat into the transition region as well. It is a tall tree, 24 to 37 meters high with a very deep taproot and wide–spreading lateral roots. Its needles are 20 to 45 centimeters long, triangular or semi–circular, persistent for 2 years and with stomata on all surfaces. This tree may live to 300 years of age. It is shade–intolerant, and highly fire–resistant due to its "grass stage" as a seedling and thick bark as a mature tree (Fowells, 1965; Harlow et al., 1979).

Chapter 4

A Biomass Production Model to Simulate Relative Competitive Ability in Different Vegetation Types

One of the basic premises of this model is that the relationship between different vegetation types can be described as competitive. This is supported by Walter (1985) who suggests that prevailing physical conditions will only be important in determining vegetation distributions in so far as they affect the relative competitive abilities of the plants. Fitter and Hay (1987) define competition as a situation where the supply of a resource is less than the joint requirement of two organisms, and as a result the performance of one or both is impaired. For plants, limiting resources may include space both above and below ground, carbon dioxide, nutrients, water, and light. This model is based on the concept that the type of plant that can produce the most biomass under a given set of environmental conditions will be the most successful at capturing these limited resources, thereby increasing its biomass even further and eventually dominating in a given location.

Light is the most critical resource for a plant, and the ability to compete for light will to a large degree influence the ultimate success of the plant. Biomass in the form of adequate leaf area will be a determining factor in successful light capture. Any limiting resource such as nutrients or water which reduces biomass production and hence leaf area will have a negative impact on the plant's overall competitive abilities (Etherington, 1982). This process has a positive feedback mechanism, as biomass production depends on carbon fixation, which depends on leaf area, which is a function of biomass. In the words of Etherington (1982), "Larger plants tend to become larger and smaller plants relatively smaller until some are eliminated".

This hypothesis suggests that competitive equilibria can be expressed in terms of the relative ability of competing vegetation types to maximize their biomass under a given set of environmental conditions. Competitive ability will be determined by such things as growing season, water–use efficiency, leaf area, and photosynthetic capacity, as functions of temperature, moisture and other environmental factors. As these factors vary spatially, the relative competitive ability of different vegetation types will also vary spatially (Walter, 1985).

Biomass production is ultimately a function of carbon assimilation through the process of photosynthesis. Carbon assimilation can be represented as the carbon absorbed per leaf area × leaf area. Water vapor and carbon dioxide exchange are directly related, as both occur through the stomata, so that we can approximate the assimilation rate by determining the evapotranspiration rate. For any species

$$A = \eta E_T(\text{soil, climate, vegetation})\ L(t\,|\,\phi) \qquad (1)$$

where

A = assimilation (mg CO_2 m^{-2} [land] day $^{-1}$)
η = water use efficiency of assimilation (mg CO_2 g^{-1} H_2O)
E_T = actual evapotranspiration (g H_2O m^{-2}[leaf] day^{-1})
L = leaf area index (m^2 [leaf] m^{-2} [land])
t = seasonal time
ϕ = geographic location (latitude, longitude, elevation)

Assimilation is also referred to as productivity. Primary productivity is defined by Whittaker (1975) as the rate at which energy is bound or organic material created by photosynthesis, per unit area, per unit time. Part of the energy fixed by plants is used by them for essential metabolic processes; this is termed respiration. Gross primary production is defined as the total rate of energy fixation by plants, and net primary production is this rate less the plant's respiration rate. Net primary production is usually expressed as grams of dry matter produced per square meter of land surface per year, and is measurable as increases in plant biomass (leaf, root and shoot), litter fall, and seed production. Net primary production is actually a more appropriate measure of competitive ability than gross assimilation because it is a direct measure of actual biomass production. We can rewrite equation (1) as

$$\mathrm{NPP} = \alpha\, E_T\, L \tag{2}$$

where

NPP = net primary productivity (g dry weight m^{-2} [land] yr^{-1})

α = water use efficiency of production (g dry weight g^{-1} H_2O)

and E_T and L are as previously defined.

The water use efficiency of productivity, α, is defined by Larcher (1983) as the amount of dry matter produced per unit of water transpired. On an annual basis, this value can be assumed to be reasonably constant for a given species. It is a function of the type of photosynthetic process employed by the plant (C–3, C–4, or CAM) and of the percentage of gross production which is consumed by respiration. All temperate forests trees use C–3 photosynthesis so that this is not likely to produce a difference in water use efficiency values. Respiration is largely a function of the relative amounts of photosynthesizing and non–photosynthesizing tissue in a plant, which are also reasonably similar in the types of trees under consideration here (Etherington, 1982).

For a given species, actual evapotranspiration (g H_2O m^{-2}[leaf] day^{-1}) can be represented as

$$E_T = k(t,L)\ E_P(t|\phi)\ C(T_a)\ W(s)\ M \tag{3}$$

where

k = crop coefficient (dimensionless)

t = seasonal time

L = leaf area index (m^2 [leaf] m^{-2} [land])

E_P = potential evapotranspiration (g H_2O m^{-2} [leaf]day^{-1})

ϕ = geographic location (latitude, longitude, elevation)

C = photosynthetic capacity ($0 \leq C \leq 1$)

T_a = air temperature (°C)

W = soil moisture factor ($0 \leq W \leq 1$)

s = soil moisture concentration (dimensionless)

M = % of total forest cover represented by this species ($0 \leq M \leq 1$)

Potential evapotranspiration (E_P) represents the upper limit of possible evapotranspiration from a given surface and is defined as the rate at which moisture would evaporate from that surface under given climatic conditions if the moisture supply was unlimited. It is a function of the energy available for evaporation, and is typically calculated using meteorological variables including net radiation, temperature, wind speed, surface roughness and relative humidity. The rate of evapotranspiration under these conditions is climatically controlled; indeed, E_P is often referred to as the atmospheric vapor transport capacity.

There are a number of factors that can reduce actual evapotranspiration (E_T) below potential at any given time:

1. The process of transpiration by plants is inextricably linked to the process of photosynthesis. Photosynthesis converts energy from the sun into energy which is useful to plants and animals by converting carbon dioxide and water to carbohydrates

and oxygen (Raven et al., 1976):

$$CO_2 + H_2O + \text{light} \rightarrow (CH_2O) + O_2 \tag{4}$$

The carbon dioxide for this process must be obtained from the atmosphere, and to enter the plant cell it must be in solution so that it can diffuse through the cell membrane, which is essentially impervious to gaseous CO_2. In order for this to occur, the carbon dioxide–containing atmosphere must come into contact with a moist cell surface. However, this exposure also leads to evaporation. Any adaptation of the plant to reduce water losses will concurrently limit carbon dioxide absorption, thus tradeoffs are made continually as the plant adjusts to changing environmental conditions.

Although the entire surface of a plant's leaf is exposed to the atmosphere, this external leaf surface is covered with a waxy cuticle that is relatively impermeable to the movement of water vapor and CO_2. Instead, tiny openings called stomata lead from the outer surface of the leaf into cavities where carbon dioxide is absorbed and water is evaporated from moist cell walls. The size of these openings and hence the circulation of air through them is regulated by guard cells which, through changes in turgor, can open and close the stomata. A complex series of biochemical processes, many of which are not well understood, regulate the turgor in the guard cells and thus the relative degree of stomatal opening (Raven et al., 1976).

In bright sunshine with ample water supply it is to the plant's advantage to have the stomata fully open, allowing for the highest possible rate of CO_2 exchange. The reverse is true at night when no CO_2 is necessary because no photosynthesis is occuring, and the stomata are fully closed (there are exceptions to this, but not in the vegetation types under consideration here). When the water supply is limited, however, the plant must balance water loss against CO_2 gain and partial or complete stomatal closure often results.

2. With few exceptions, all of the water transpired by plants is absorbed from the soil through the root system. Soil properties are very important in determining the amount of water that can be stored in the soil and how much of that water may be available for uptake by the plant. In addition, soil properties may affect the extent of a plant's root system, as well as how fast water can move to the roots during active transpiration. Soils are typically described by their texture, which is a function of the distribution of particle sizes in the soil. Larger particles are termed sands, medium particles are silts, and small particles are clays. The relative mixture of these particles will be a major factor in determining other soil properties.

Soil porosity, n, is defined as the ratio of pore volume to the total volume of a given soil. Porosity varies from 0.3 to 0.6 in most natural soils, with coarse–textured soils having larger pores but lower total porosity than fine–textured soils. Relative saturation, s, is defined as the ratio of the volume of water to the volume of pore space in the soil at any given time. When all of the pore space is filled with water, the soil is said to be saturated and s is equal to one. Conversely, when the soil is completely dry and all of the pore space is filled with air, s is equal to zero.

At anything less than complete saturation, it takes a certain amount of energy to remove moisture from the soil. This energy is termed soil water potential, ψ, and is expressed in negative pressure units. The drier the soil becomes, the more negative the soil water potential becomes, as larger and larger amounts of energy are required to remove the remaining water (Hillel, 1971). The relationship of ψ and s varies with soil texture, and this relationship is known as the soil moisture retention curve (Figure 3, from Brady, 1974).

Water can only move along a gradient from high potential energy to low potential energy. This means that for transpiration to occur, the water potential must steadily decrease from the soil through the plant to the atmosphere. This is often called the "soil–plant–atmosphere continuum". Within a limited range of water potentials, the plant maintains normal activity and transpiration proceeds at a maximum rate (if no other factors are limiting). When the soil becomes dry, and water potential values in the plant drop below a certain critical value, this is a signal to the plant of impending water stress. At this point, the stomata typically begin to close. As the soil continues to dry, a second threshhold value of ψ will be reached at which time the plant can no longer extract water from the soil, the stomata will close completely, and transpiration will cease. This value is termed the permanent wilting point in the agricultural literature. Figure 4 illustrates the observed effect of reductions in soil moisture on transpiration and photosynthesis for three tree species (Havranek and Benecke, 1978).

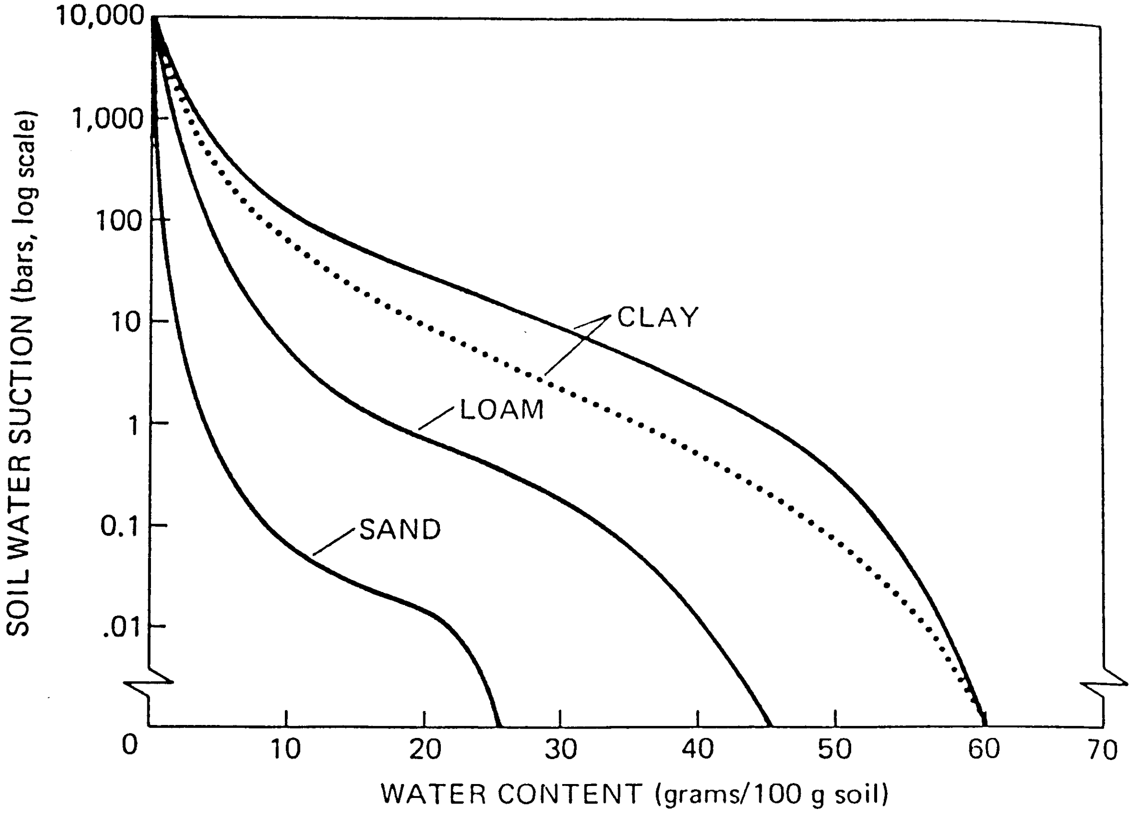

Figure 3: Typical soil moisture retention curves for three soil textures (Brady, 1974).

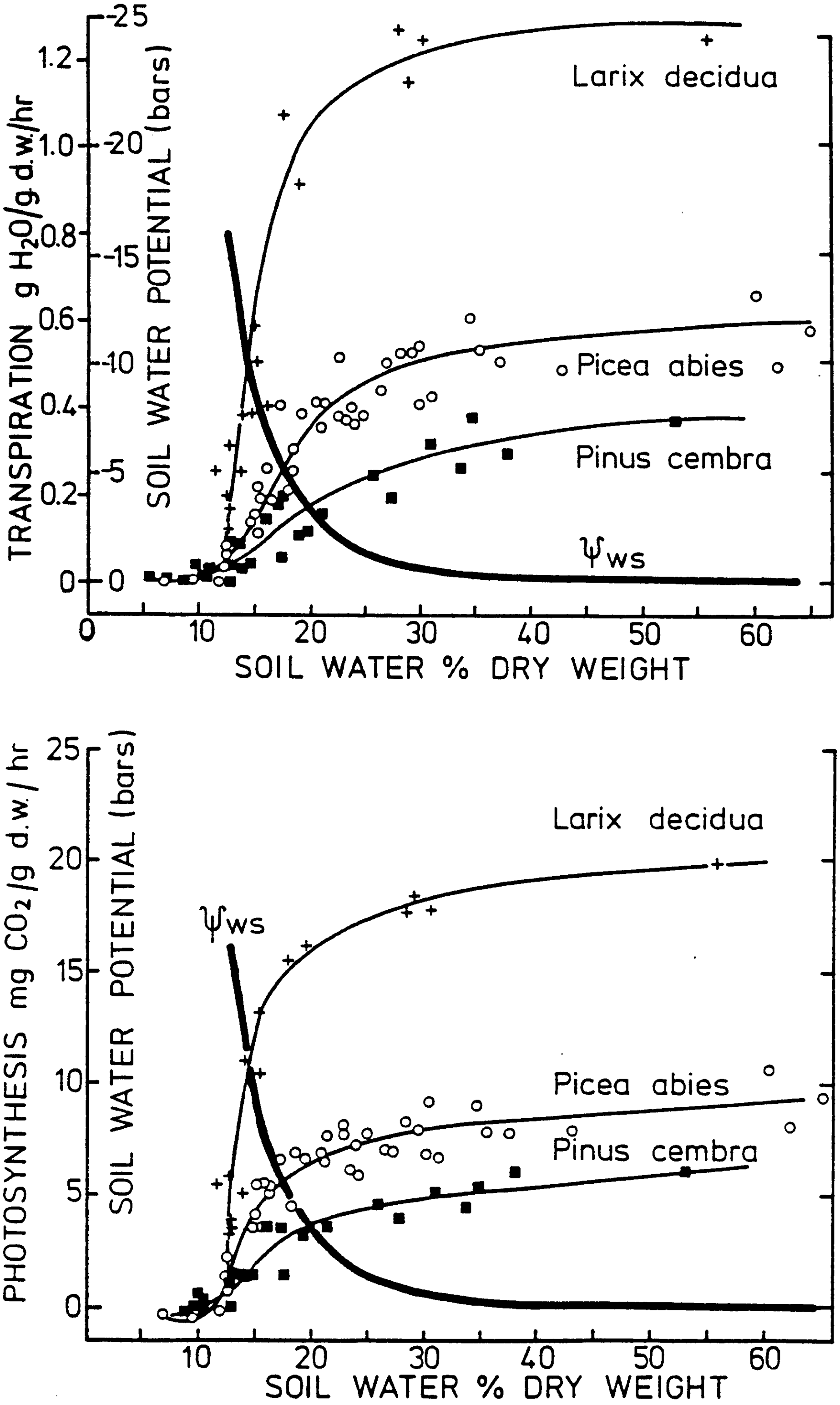

Figure 4: The effect of soil moisture content on transpiration (top) and photosynthesis (bottom) in three conifers (Havranek and Benecke, 1978).

The soil moisture multiplier, W, reflects the effect of partial or complete stomatal closure on the transpiration rate. W is a function of the vegetation type and soil water potential, which is in turn a function of soil moisture content and texture.

3. Water limitations are not the only reasons for reductions in the evapotranspiration rate below its potential value. Even under conditions of adequate soil moisture, high vapor pressure deficits, low soil or air temperatures, low light levels or rapid transpiration leading to moisture deficits adjacent to the roots may cause partial or complete stomatal closure (Davies and Koslowski, 1974; Davies et al., 1981; Losch and Tenhunen, 1981; Farquhar and Sharkey, 1982; Schulze and Hall, 1982; Marshall and Waring, 1984; Sheriff, 1984; Lindroth, 1985; Smith, 1985; Schulze, 1986). In addition, while the canopy is wet, available energy will be used for the evaporation of intercepted rainfall and transpiration will be reduced or halted until the canopy is dry (cf. Stanhill, 1973).

Since many of these processes are not well understood, and since these changes can occur very rapidly, it is difficult to incorporate these relatively instantaneous processes into a model which computes E_T on an hourly or daily basis. The agricultural sciences have developed the concept of a crop coefficient to approximate the effect of these processes, and we follow their example here.

The crop coefficient (k) represents the time averaged effects of these factors on evapotranspiration under otherwise favorable (i.e. well–watered) conditions. It is defined here as

$$k = E_T / E_P \tag{5}$$

when no other conditions are limiting, although in the agricultural literature it also reflects the effects of diminishing soil moisture (cf. Hargreaves, 1966; Doorenbos and

Pruitt, 1977; Shuttleworth, 1979). As defined here, k is an average annual value for a given type of vegetation, and it is expected to be somewhat less than one.

4. Seasonal changes affect daily E_T by determining the length of the active photosynthetic period, which is also the active transpiration period. With few exceptions (Perry, 1971b), photosynthesis in trees occurs primarily in the leaves. Deciduous trees have leaves for only a portion of the year, whereas the conifers have leaves all year. In deciduous trees, the timing of leaf emergence is primarily affected by temperature (Perry, 1971a; Flint, 1974; Nooden and Weber, 1978; Etherington, 1982; Powell, 1987), whereas leaf color change is primarily related to photoperiod (Wareing, 1956; Downs, 1962; Perry, 1971a; Addicott and Lyon, 1973; Flint, 1974; Nienstaedt, 1974; Villiers, 1975; Vince–Prue, 1975; Nooden and Weber, 1978; Etherington, 1982), both of which are ultimately a function of latitude. The presence or absence of leaves is represented in the model through the use of the leaf area index multiplier, L.

5. Although conifers do not lose their leaves during the winter, low temperatures can reduce or completely prohibit photosynthesis and likewise transpiration (Koslowski, 1943; Freeland, 1944; Bourdeau, 1959; Parker, 1961; Pisek, 1973; Vowinckel et al., 1975; Larcher, 1983). In addition, the physiological changes that northern species undergo in their annual process of cold acclimation often reduces their photosynthetic capacity even during winter warm spells (Woodward, 1987). Transpiration may also be prevented solely by the physical restriction of the water in the soil or in the tree being frozen. This can also restrict the transfer of carbon dioxide. All of these considerations are accounted for in the model by the photosynthetic capacity coefficient C.

In general, for any given plant at a specific season and time in its life cycle, there is some optimum temperature at which photosynthesis will proceed at a maximum rate if other factors such as light are not limiting. This optimum is primarily related to the enzymatic steps involved in the photosynthetic process. Chemical, enzyme–catalyzed reactions will proceed faster with increasing temperatures, but certain enzymes will be deactivated at high temperatures. The balance between these factors will determine the location of the optimum (Oquist, 1983). At lower or higher temperatures, photosynthesis will be reduced and eventually stop entirely. Figure 5 illustrates the shape of this relationship for several different tree species (Larcher, 1969).

This optimum is not necessarily constant, but may shift with the seasons as the plant acclimates to changing average temperatures. Figure 6 illustrates this process for loblolly pine (Strain et al., 1976). Oquist (1983) notes that the optimum temperature is typically a few degrees higher than the temperature at which plants are acclimated. Brubaker (1986) points out that genetic diversity allows for different enzymes to be utilized at different temperatures which may account for some of the observed acclimation.

6. The percent cover factor, M, becomes important when two vegetation types are actively competing. For a closed canopy of two vegetation types in a specific location,

$$NPP(\phi) = \int_{\tau_a} NPP_a(t \mid \phi)\, dt + \int_{\tau_b} NPP_b(t \mid \phi)\, dt \qquad (6)$$

where

$NPP(\phi)$ = net primary productivity (g dry weight m^{-2}[land] yr^{-1})

τ = growing season (days)

and subscripts a and b represent values for the two competing vegetation types.

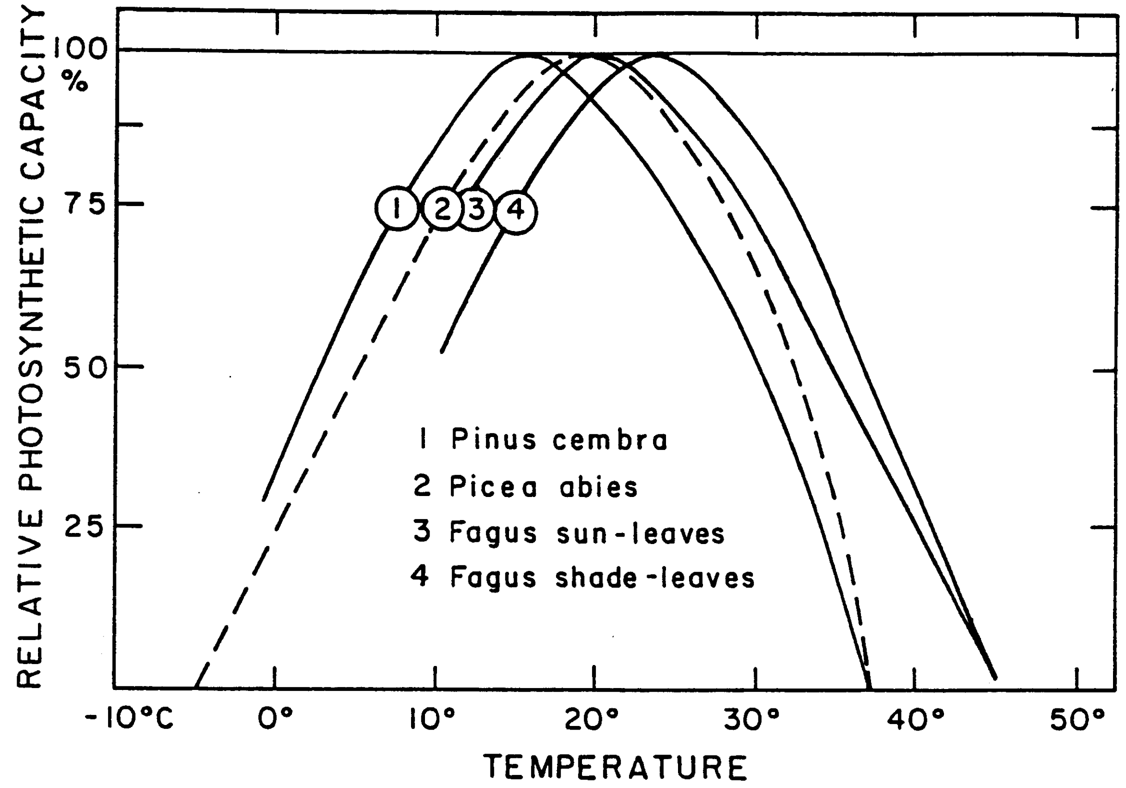

Figure 5: Temperature dependence of photosynthesis in three temperate forest trees (redrawn from Larcher, 1969).

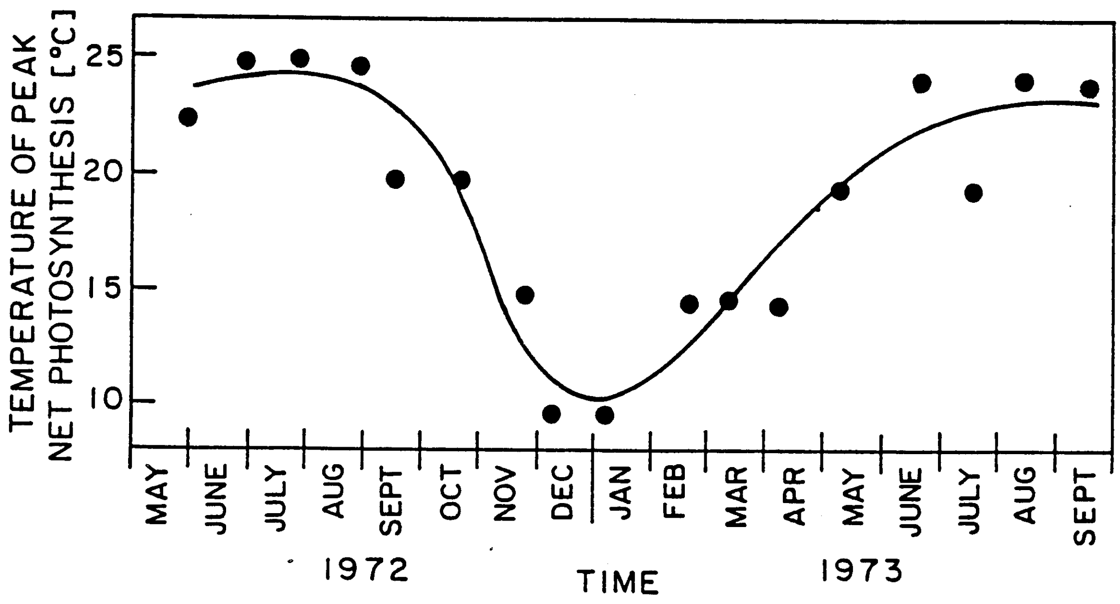

Figure 6: Temperature of maximum net photosynthesis of the same loblolly pine needles during two growing seasons and one winter (Strain et al., 1976).

The closed forest assumption gives

$$M_a + M_b = 1 \tag{7}$$

Assuming that net productivity as represented by NPP is an adequate surrogate for biomass production and hence relative competitive ability, then in any given environment the mixture of vegetation types should be such that NPP is maximized. This gives

$$\frac{\partial NPP(\phi)}{\partial M_a} = 0 \quad \text{or} \quad \frac{\partial NPP(\phi)}{\partial M_b} = 0 \tag{8}$$

Using equations (2) and (3) in (6) and differentiating according to equation (8), the competitive equilibrium between the two vegetation types is given by

$$\int_{\tau_a} \alpha_a k_a E_P C_a W_a L_a \, dt = \int_{\tau_b} \alpha_b k_b E_P C_b W_b L_b \, dt \tag{9}$$

To determine the exact location of the boundary between vegetation types a and b, one need only solve the above equation for latitude! However, in this form it is not particularly tractable, therefore some simplification is required. Figure 7 shows the anticipated results of the solution of equation (2) for hypothetical vegetation types a and b over a range of latitudes. The latitude where the curves for the two vegetation types cross is the expected location of the ecotone, and this is essentially a graphical method of solving (9).

To produce this type of plot for the vegetation types under consideration, we use equations (2) and (3) to write the net annual primary productivity for a closed forest (M=1) of species j as

$$NPP_j(\phi) = \alpha_j k_j \sum_{i=1}^{365} C_{j_i} W_{j_i} L_{j_i} E_{P_i}(\phi) \tag{10}$$

where all parameters are as previously specified. Values of C, W, L and E_P are computed daily, whereas α and k are vegetation–specific annual values.

Chapter 5 summarizes the methods used to estimate parameters for the model, and Chapters 6 and 7 explore the use of the model to predict ecotone locations.

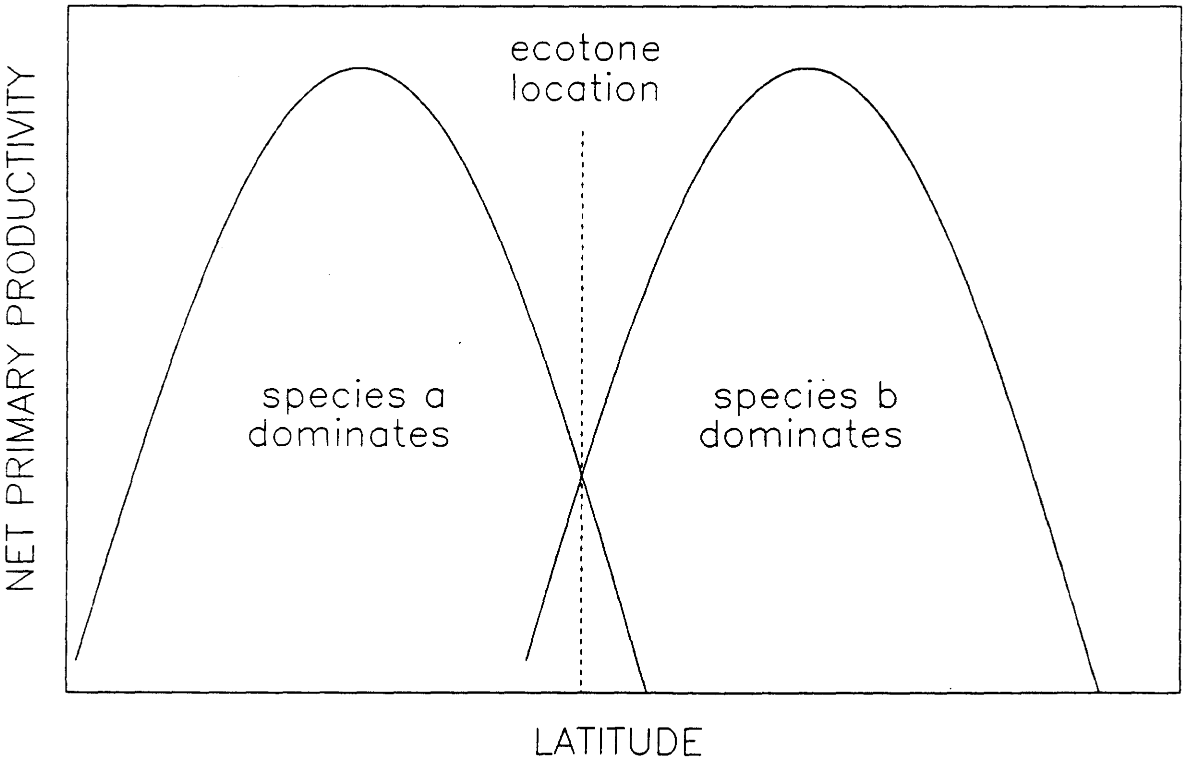

Figure 7: Hypothetical relationship of net primary productivity and latitude for two competing vegetation types.

Chapter 5

Estimation of Model Parameters

This chapter presents an overview of the components of the productivity model. It includes a detailed description of each parameter that is included in the model, and how their values were obtained. The section also contains a detailed discussion of the climatic data used to run the model.

5.1 Climatic Data

To produce a diagram similar to Figure 7, productivity values must be computed for climatic conditions at locations throughout eastern North America. Several criteria were considered in selecting a climatic data set to use for these computations.

There are two classes of climatic conditions which can affect plant physiological processes, one being average conditions experienced by the plant year after year, and the other being extreme conditions which may occur only occasionally during a plant's lifetime. There are certain critical times in a plant's life cycle when extreme conditions may be a deciding factor in whether it survives or not. These occur primarily during seed germination and establishment, when certain levels of temperature and moisture may be absolutely necessary for survival (Harper, 1977; Etherington, 1982; Hom and Oechel, 1983). After these first critical years, however, an occasional drought or cold winter may reduce a tree's annual growth but is unlikely to kill it. In fact, Brubaker (1986) states that trees can survive long periods of marginal climate in the reproductive phase of their life cycle, although reproduction will be curtailed under these conditions (Black and Bliss, 1980).

It seems appropriate to consider average conditions as the determining criteria for the presence or absence of a particular vegetation type due to competition at a specific location. Etherington (1982) states, "...it is reasonable to assume that the system best adjusts vegetative growth and reproduction to the average of many seasons' climatic oscillation". Since mature trees will produce seed regularly, a bad year or two will not affect the long term viability of that species in a region, but ongoing adverse conditions will eventually reduce its competitive ability, reproduction, and ultimately its survival in that location. An example of this can be seen in at least two locations along the tree line in the Northwest Territories, Canada, where there are mature trees but no new sexual reproduction due to changing climatic conditions in the region (Elliott, 1979; Black and Bliss, 1980).

A second criterion in the selection of a data set was its availability on magnetic media. The quantity of data necessary for the range of calculations desired would have made manual data entry prohibitively time consuming and error–prone. Another consideration was that of data frequency. Due to the nature of the computations involved in calculating E_P, growing season, and photosynthetic efficiency (discussed later in this section), monthly data were too infrequent for use in the model. Hourly data, on the other hand, greatly increase the number of calculations that must be made, and are not available for enough locations to be useful. That left daily data as the logical choice.

Finally, the question of what measurements were important was considered. While variables such as wind speed, relative humidity, and net radiation would have permitted more accurate E_P calculations, they are not available for a large number of stations. The key variables that were finally settled on consisted of daily minimum, maximum and average temperature, and daily precipitation.

The data set that met all of these requirements was "Daily Normals of

Temperature, Precipitation and Degree Days", which we obtained from the National Climatic Data Center in Asheville, North Carolina. The normals were computed for the time period 1951 to 1980. The daily values in the file are not simple means of the observed daily values but are interpolated from the monthly means using a spline function (U.S. National Environmental Data Referral Service, 1984). Information about the locations and names of the stations included in the data set was obtained from the U.S. National Climatic Data Center (1983a). Out of this data set, 167 stations in 31 states were used for model calculations. Information about the selected stations is tabulated in Table 1 of Appendix A. All stations selected were east of 97° W longitude.

The U.S. data set was supplemented with daily normal data for the same time period from 6 Canadian cities (Atmospheric Environment Service, 1982a,b,c,d,e,f). These data were also smoothed, however the methods used are not documented in the source publications. Canadian station information is also summarized in Appendix A, Table 1, and the actual data are provided in Appendix A, Table 7.

5.2 Potential Evapotranspiration (E_P)

The combination method developed by Penman (1948) is perhaps the most widely used method of computing E_P, however, it requires the measurement or estimation of a number of meteorological variables which makes it difficult to evaluate over the wide range of conditions encountered in this model. Fortunately, there are also a number of empirical relationships for estimating E_P which require smaller numbers of variables.

The data set being used for the model restricts the options for estimating E_P to those which use only air temperature and other easily obtained coefficients. The empirical relationship of Hamon (1961) was selected for its simplicity and ease of calculation. Hamon's equation, converted to metric units for daily computation, is

$$E_P = x\,y^2\,\rho_s \tag{11}$$

where

E_P = potential evapotranspiration (cm day^{-1})
x = 9.7 x 10^{-2} (m^3 cm day kg^{-1} hr^{-2})
y = possible amount of sunshine (hr day^{-1})
ρ_s = saturated vapor density at mean daily air temperature (kg m^{-3})

The model uses a routine modified from Curtis and Eagleson (1982) to compute y from latitude and time of year. Saturated vapor density is defined as

$$\rho_s = \frac{0.622 e_s}{RT} \tag{12}$$

where

e_s = saturated vapor pressure at mean daily surface temperature (Pa)
R = dry air gas constant (287 J kg^{-1} K^{-1})
T = absolute mean daily surface air temperature (K)

Numerous expressions exist for computing e_s from temperature. This model uses

$$e_s \cong 2.5605\mathrm{x}10^{11} \exp(-5423/T) \tag{13}$$

which is an approximation from Rogers (1979).

Hamon's (1961) equation was originally formulated for use with monthly averages, whereas the productivity model uses daily data. A comparison of E_P values computed by the model with published evaporation data (Farnsworth and Thompson, 1982; Farnsworth et al, 1982) showed that the model consistently underestimated E_P. Actual annual free water surface evaporation was determined for 109 stations by multiplying recorded pan evaporation (Farnsworth and Thompson, 1982) by a coefficient obtained from an atlas (Farnsworth et al, 1982). These values were compared to model E_P computations for the same stations, and a factor

$$F = \frac{E_P \text{ (actual)}}{E_P \text{ (model)}} \tag{14}$$

was computed. Table 2 in Appendix A summarizes actual and computed values of E_P along with the computed value of F for each station. This factor was plotted against latitude (Figure 8), and a regression analysis was performed, which produced the relationship

$$F = 0.92 + 0.01\phi, \qquad R^2 = 0.49 \tag{15}$$

where ϕ is latitude. All E_P values computed by the Hamon (1961) method on a daily basis are now adjusted by this factor.

5.3 Leaf Area Index (L)

In most literature, leaf area index is defined as either one–sided leaf surface area per unit area of ground surface or total leaf surface area per unit area of ground surface. For deciduous forests, where leaves typically have stomata only on one side, the one–sided area is usually reported and averages about 5. For conifers, which typically have stomata on all leaf surfaces, total leaf area is usually reported, and this value ranges from 5 to 10. Cannell (1982) cites conversion ratios of total leaf area to one–sided leaf area of 2.8 for pines and 2.3 for other conifers. Table 2 summarizes values for complete canopies gathered from the literature for deciduous and coniferous forests. Leaf area indices reflect the degree of canopy cover, and in situations where cover is less than 100 percent, leaf areas will typically be less than 5.

Saxton and McGuiness (1982) report that a leaf area index value greater than 3 has no additional effect on evapotranspiration in crop plants, and Mooney (1972) states that the optimum leaf area for photosynthesis is around 5. In applying these observations we reason that the purposes of leaf area indices greater than one is to provide the multiple surface orientations necessary to maintain optimum

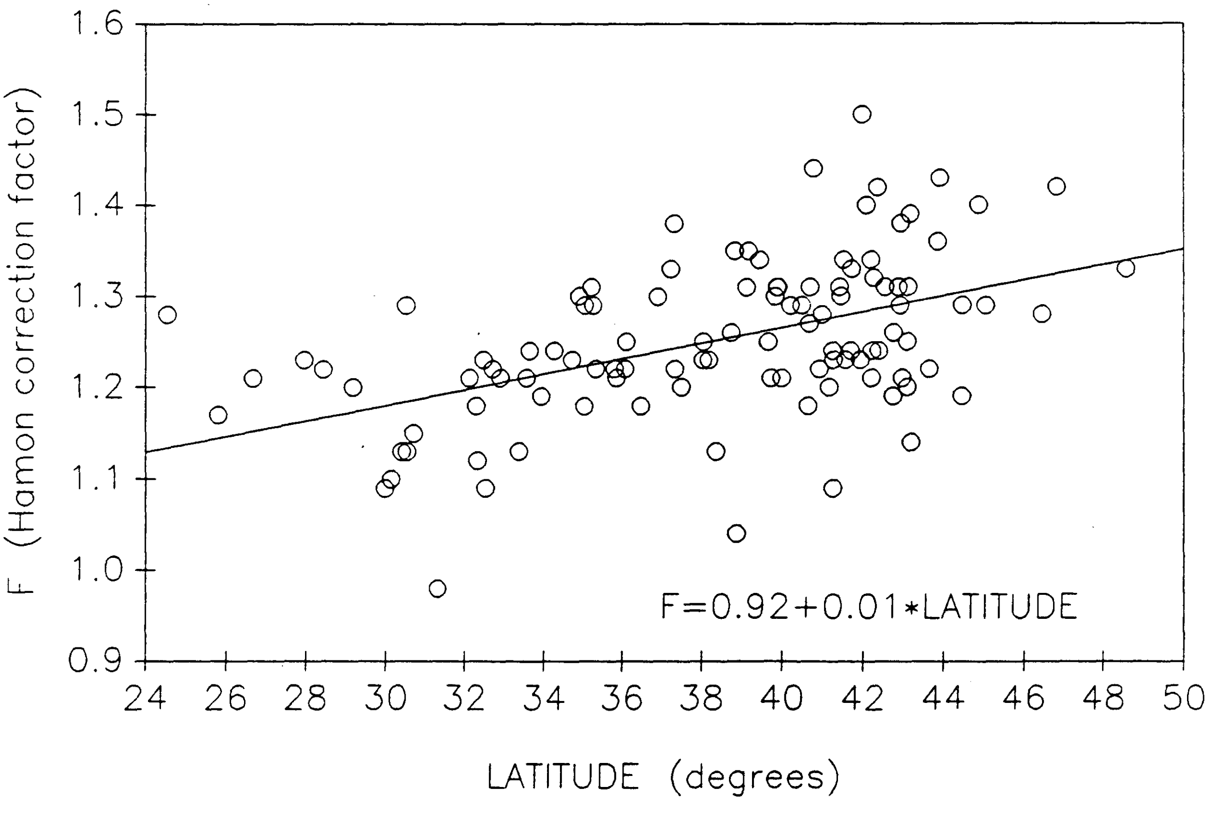

Figure 8: Hamon adjustment factor F versus latitude.

Table 2
Leaf Area Indices Reported in the Literature

Eastern Deciduous Forest

Source	Species	Location	Forest Description	LAI*
Whittaker, 1963 & 1966	horse chestnut, hemlock	Smoky Mountains, NC	1310 m elevation	6.2
Whittaker, 1963 & 1966	chestnut oak, red maple	Smoky Mountains, NC	820 m elevation	6.3
Monk et al., 1970	oak–hickory	Athens, GA		4.0
Aber, 1979	beech–birch–maple	NH	mixed hardwood	4.5–7.5
DeAngelis et al, 1981	tulip poplar, oak, hickory	Oak Ridge, TN	mixed mesic deciduous	5.1
DeAngelis et al, 1981	oak	Noe Woods, WI	forest–prairie border	4.4
Cannell, 1982	beech–birch–maple	Hubbard Brook, NH	83 yrs, 500–630 m elevation	5.5
Cannell, 1982	beech–birch–maple	Hubbard Brook, NH	95 yrs, 630–710 m elevation	5.7
Cannell, 1982	beech–birch–maple	Hubbard Brook, NH	124 yrs, 710–785 m elevation	6.2
Cannell, 1982	tulip poplar, oak	Oak Ridge, TN	40–48 years	5.6–6.0
Baldocchi et al, 1987	oak & hickory	Oak Ridge, TN	uneven–age, natural stand	4.9
Monk & Day, 1988	red maple, oak	Coweeta, NC	mixed hardwood, watershed 18	6.2

Boreal Forest

Source	Species	Location	Forest Description	LAI*
Whittaker, 1963 & 1966	Fraser fir, red spruce	Smoky Mountains, NC	1800 m elevation	14.8(T)
Whittaker, 1963 & 1966	Fraser fir	Smoky Mountains, NC	1920 m elevation	12.3(T)
Weetman & Harland, 1964	black spruce	Baie–Comeau, Quebec	65 years	9.8(T)
Cannell, 1982	mixed boreal	Huntsville, Ontario	84 years	11.6(O)
Cannell, 1982	mixed boreal	Huntsville, Ontario	130 years	7.1(O)
Cannell, 1982	mixed boreal	Huntsville, Ontario	212 years	16.9(O)
Cannell, 1982	mixed boreal	Huntsville, Ontario	246 years	15.0(O)

Southern Pine Forest

Source	Species	Location	Forest Description	LAI*
Whittaker, 1966	pine	Smoky Mountains, TN	610 m elevation	7.8(T)
Jarvis et al., 1976	loblolly pine	Chapel Hill, NC		2.6(O)
DeAngelis et al., 1981	Eastern white pine	Coweeta, NC	plantation, watershed 1	17.8(T)

*LAI is measured as one side of the leaves in deciduous trees. In conifers, it is measured as either one sided (O) or total (T) leaf surface area.

photosynthetic rates at all sun angles (Horn, 1971; Chabot and Hicks, 1982). For the purposes of estimating evapotranspiration, however, we can assume that the average *effective* leaf area index is unity for a fully leaved tree in a closed forest. It follows that for coniferous trees, L will be 1 all year, whereas for deciduous trees L will be 0 during the winter, 1 during the growing season, and between 0 and 1 in the spring and fall transition periods.

5.4 Growing Season (τ)

To aid in computing the length of the growing season, phenological data were gathered from the literature for red oak and other species for a number of locations and dates (Tables 3 and 4). Temperature data for the nearest recording station for the corresponding years were also obtained (Appendix A, Table 3). A number of different relationships were considered for predicting bud break in the spring, including Julian day versus latitude, average temperature on day of bud break versus latitude or alone, and accumulated growing degree days with various threshholds and starting points.

Degree days are computed by subtracting a specified threshhold temperature from the daily average temperature, and if the remainder is positive it is added to the sum, which is started at a specified time of year. This is a common means of predicting budbreak and other phenological events (cf. Valentine,1983; Lechowicz, 1984), and it was the method finally selected for use in the model. No significant variation was found with latitude, and the smallest variance in the different trials was obtained using a threshhold of 5 °C and a starting date of February 1 (Julian day 32) for cumulation, which produced a result of 194 degree days necessary for bud break (Table 3).

Table 3
Spring Phenological Data

Location	Latitude (°N)	Elevation (m)	Year	Julian Day of bud break	Julian Day of full leaf	difference	accumulated degree days	Source
Wauseon, OH	41.60	243	1883	133	154	21	217	Smith, 1915
Wauseon, OH	41.60	243	1884	128	143	15	171	Smith, 1915
Wauseon, OH	41.60	243	1885	136	149	13	193	Smith, 1915
Wauseon, OH	41.60	243	1886	114	140	26	188	Smith, 1915
Wauseon, OH	41.60	243	1887	125	147	22	193	Smith, 1915
Wauseon, OH	41.60	243	1888	132	150	18	215	Smith, 1915
Wauseon, OH	41.60	243	1889	128	137	9	228	Smith, 1915
Wauseon, OH	41.60	243	1890	124	148	24	193	Smith, 1915
Wauseon, OH	41.60	243	1891	119	142	23	185	Smith, 1915
Wauseon, OH	41.60	243	1892	135	160	25	216	Smith, 1915
Wauseon, OH	41.60	243	1893	132	157	25	213	Smith, 1915
Wauseon, OH	41.60	243	1894	123	142	19	282	Smith, 1915
Wauseon, OH	41.60	243	1895	123	136	13	222	Smith, 1915
Wauseon, OH	41.60	243	1896	116	131	15	207	Smith, 1915
Wauseon, OH	41.60	243	1897	145	127	18	205	Smith, 1915
Wauseon, OH	41.60	243	1898	130	148	18	294	Smith, 1915
Wauseon, OH	41.60	243	1899	117	134	17	193	Smith, 1915
Wauseon, OH	41.60	243	1912	127	146	19	182	Smith, 1915
Cream Hill, CT	41.87	396	1937	120			81	Kienholz, 1941
Cream Hill, CT	41.87	396	1938	111			148	Kienholz, 1941
Cream Hill, CT	41.87	396	1939	121			89	Kienholz, 1941
Wisconsin Dells, WI	43.63	268	1936	131			190	Leopold & Jones, 1947
Wisconsin Dells, WI	43.63	268	1937	128			129	Leopold & Jones, 1947
Wisconsin Dells, WI	43.63	268	1944	138			227	Leopold & Jones, 1947
Madison, WI	43.13	261	1959	117			89	Lechowicz, pers. comm.
Ann Arbor, MI	42.28	265	1967	135	151	16	300	Zasada & Zahner, 1970
Asheville, NC	35.43	652	1972	101			182	McGee, 1975
Asheville, NC	35.43	652	1974	95			280	McGee, 1976
Asheville, NC	35.43	652	1975	91			161	McGee, 1976
Columbia, MO	38.82	270	1976	81			177	Hinckley et al., 1979
Ithaca, NY	42.45	292	1983	135			171	Lechowicz, pers. comm.
					Averages:	19	194	

For each day, degree days are computed as

$$\begin{aligned} DD &= T_a - 5.0 \qquad && \text{if } T_a > 5.0 \\ DD &= 0 && \text{if } T_a \leq 5.0 \end{aligned} \tag{16}$$

where T_a is average daily temperature (°C), and DD is always an integer. Starting on February 1, each day's degree days are cumulated until the total reaches 194. The day on which this occurs is taken as the beginning of bud break.

A certain amount of time is then necessary for the tree to develop its full complement of leaves. Very little information is available about the nature of this process, however, Taylor (1974) presents a curve of percent leaf emergence against elapsed time for yellow poplar (*Liriodendron tulipifera* L.) which we have used as a model. The average number of days elapsed from budbreak to full leaf was computed from the phenological data as 19 days (Table 3). This was then fit to the Taylor (1974) curve, with the following result:

$$p = \tanh (0.17\, e) \tag{17}$$

where p equals the percentage of leaves emerged ($0 \leq p \leq 1$) and e equals the number of days elapsed from the day of budbreak (Figure 9).

Since leaf color change is primarily a function of photoperiod, which is in turn directly a function of latitude, the date of leaf color change was determined from a linear regression of the day of color change against latitude (Table 4, Figure 10). This relationship is

$$CC = 392 - 2.8\, \phi \tag{18}$$

where CC is the day of initial color change and ϕ is latitude.

Gee and Federer (1972) have shown that transpiration ceases shortly after color change begins. Photosynthesis also ceases, as chlorophyll and other nutrients are removed from the leaves prior to senescence (Mitchell, 1936). Although data are scarce, color change takes approximately 17 days to complete (Table 4). Due to the complete lack of more specific information, this transition is assumed to be linear. In the model it is represented as L going from a value of one on the day that color change begins to a value of zero 17 days later.

To summarize, in deciduous trees, L is 0 from the beginning of the calendar year until the day on which 194 degree days as computed by equation (16) have accumulated. L then goes from 0 to 1 over the course of 19 days following the curve defined in equation (17). It remains at a value of 1 until the day in the fall specified by equation (18), at which time it decreases linearly to a value of 0 over the next 17 days. It then remains 0 for the remainder of the year.

Model runs for different latitudes compared with information from various sources regarding the length of the growing season indicates that the model successfully predicts the length of the growing season (Britton, 1878a, 1878b; Nemeth, 1973; Federer and Lash, 1978). However, caution is necessary when making these

Table 4

Fall Phenological Data

			Julian Day of			
Location	Latitude (°N)	Species	First color	full color	difference	Source
Columbia, MO	38.80	red oak	290			Hinckley et al., 1979
Hubbard Brook, NH	43.95	yellow birch	261	275	14	Gee & Federer, 1972
Hubbard Brook, NH	43.95	beech	261	281	20	Gee & Federer, 1972
Ely, MN	47.90	bur oak	259	278	19	Ahlgren, 1957
Ely, MN	47.90	yellow birch	255	273	18	Ahlgren, 1957
Ely, MN	47.90	red maple	268	282	14	Ahlgren, 1957
			Average		17	

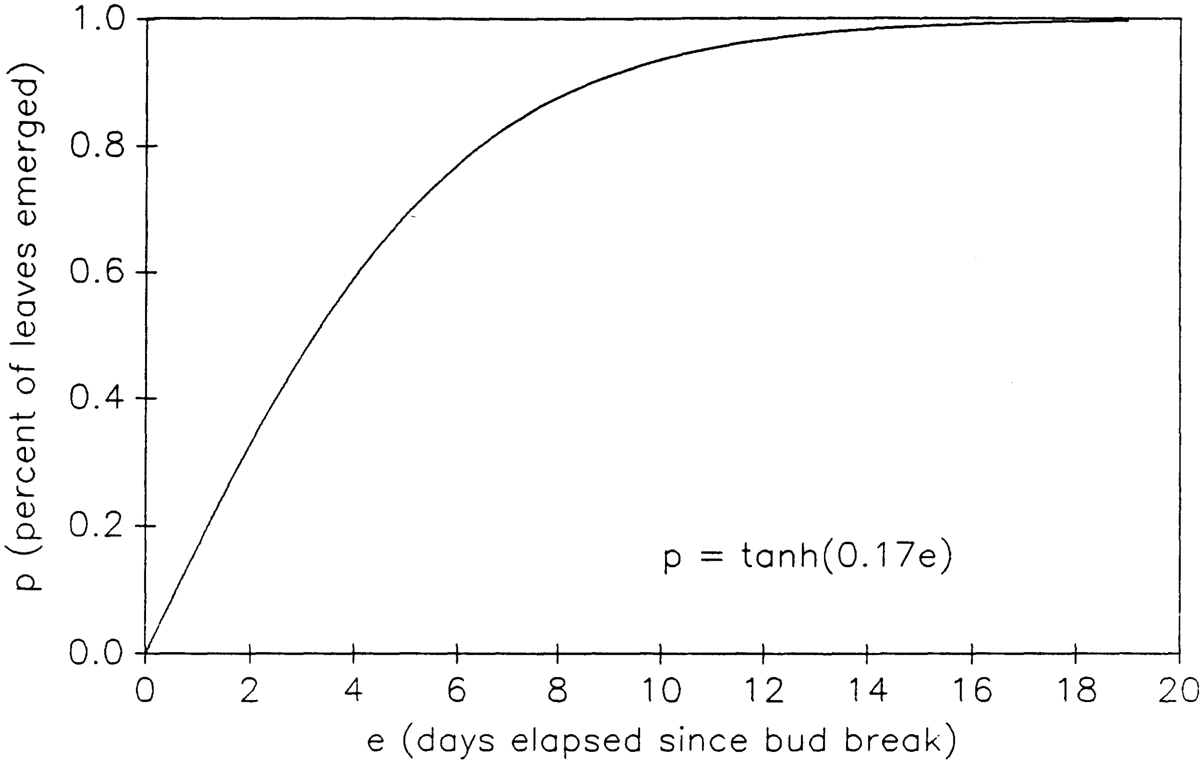

Figure 9: Leaf emergence versus time (adapted from Taylor, 1974).

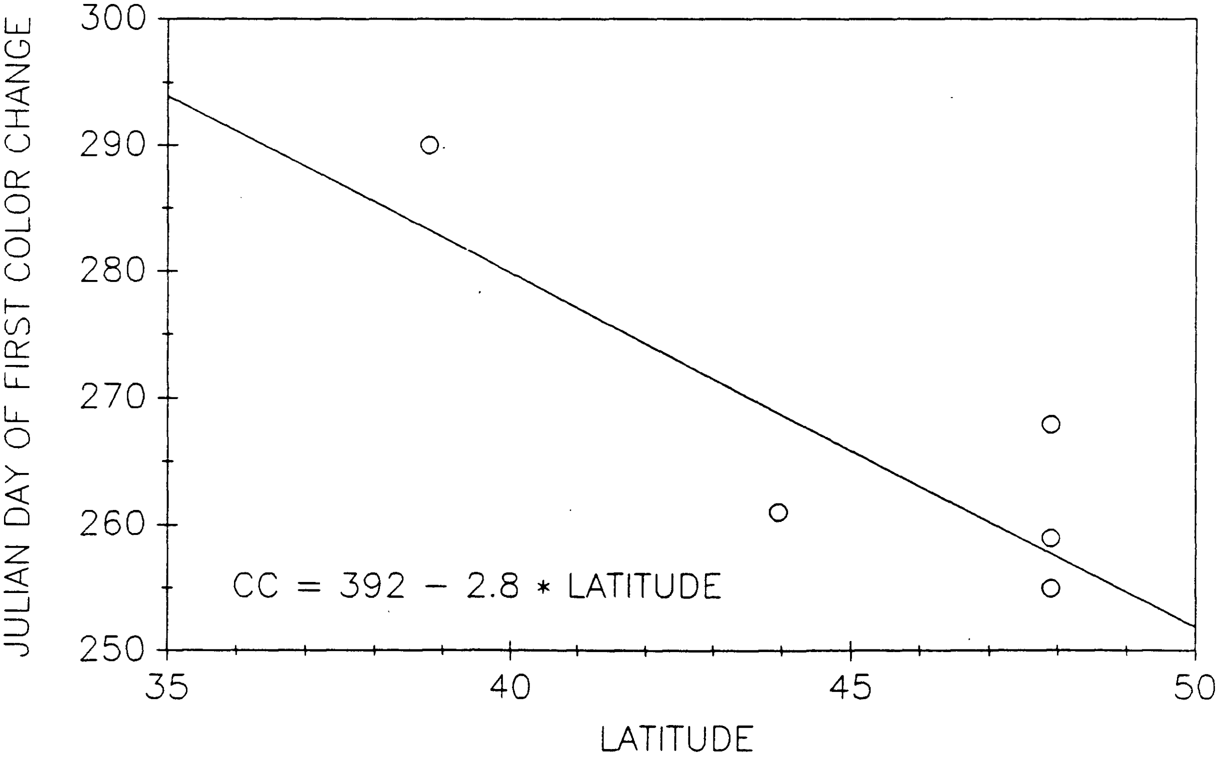

Figure 10: Day of leaf color change versus latitude

comparisons, because "length of growing season" is not always clearly defined by these authors.

5.5 Photosynthetic Capacity (C)

Table 5 contains a summary of the information available in the literature regarding temperature criteria for photosynthesis in spruce and pine. Using this information, and curves from other sources (Pisek, 1973; Larcher, 1983), the relationships shown in Figure 11 were developed to represent changing photosynthetic capacity in the model. The temperature criterion is supplemented by an additional restriction that C is always equal to zero on any day when both maximum and minimum daily temperatures fall below 0 °C.

The plateau at the level where C is equal to 1 is designed to account for the shifts in optimum temperature as the season progresses, and to reflect the statement

Table 5

Temperature Limitations on Conifer Photosynthesis

Boreal Conifers:

		Temperature (°C)			
Species	Location	Minimum	Optimum	Maximum	Reference
Black spruce	Schefferville, Que	–2	9–23	>40	Vowinckel et al., 1975
Black spruce	Evanston, IL	–6			Freeland, 1944
Black spruce	Inuvik, N.W.T.	<0	15	>35	Black & Bliss, 1980
Black spruce			16–26		Manley & Ledig, 1979
White spruce	Syracuse, NY		18–20		Larcher, 1969

Pines:

		Temperature (°C)			
Species	Location	Minimum	Optimum	Maximum	Reference
Longleaf pine	New Haven, CT	0			Parker, 1961
Loblolly pine			10–25		Strain et al., 1976
Loblolly pine		0			Kozlowski, 1943
Scotch pine		–3		37	Pisek, 1973

by Vowinckel et al. (1975) that temperature is unimportant in affecting daily photosynthesis totals for black spruce during the summer. The relationship is portrayed as linear due to the fact that the curves shown in most diagrams are linear through a large part of their range, and because there were insufficient data to warrant any other treatment. The curves are approximate, especially because average daily temperatures are being used to determine C, but they serve to place reasonable restrictions on the photosynthetic period for conifers, especially in the northern latitudes.

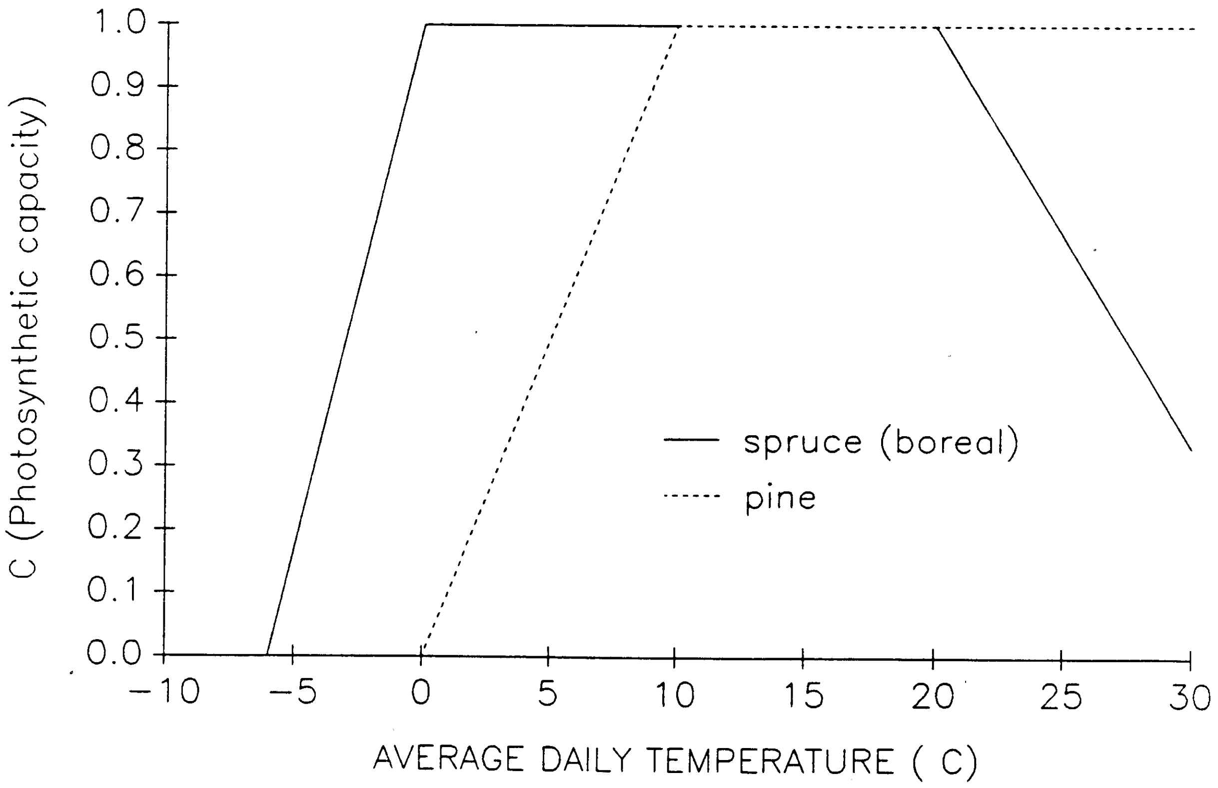

Figure 11: Relationship of photosynthetic capacity to temperature.

5.6 Water Use Efficiency (α)

Larcher (1983) provides α values for deciduous trees of between 2.86×10^{-3} and 5.0×10^{-3} g dry matter per g H_2O transpired, and α values for conifers of between 3.3×10^{-3} and 5.0×10^{-3} g dry matter per g H_2O transpired. However, since the model was fitted with net primary productivity values for above–ground production only, it was necessary to adjust these somewhat for neglecting below–ground (root) production. A review of Cannell (1982) indicates that between 13 and 35 percent of total net primary production is below–ground production. This produces revised α values of between 1.9×10^{-3} and 4.3×10^{-3} g dry matter per g H_2O transpired. The midpoint of these values is $\alpha = 3 \times 10^{-3}$ g dry matter per g H_2O transpired and this was selected for use in the model.

5.7 Crop Coefficient (k)

Although widely used in the agricultural literature (cf. Hargreaves, 1966; Doorenbos and Pruitt, 1977), values of k for forest trees are nonexistent. Our only recourse was to estimate k from existing forest measurements. The method used to accomplish this consisted of rearranging equation (10) as follows:

$$k = \frac{NPP}{\alpha \sum_{i=1}^{365} L_i \; C_i \; E_{P_i}} \tag{19}$$

with all terms defined as in Chapter 4. Because k is defined for conditions of adequate moisture, W here is equal to one and is therefore eliminated from the equation.

Measured above–ground net primary productivity data were then collected from the literature for a total of 31 locations, including 5 boreal, 12 deciduous, and 14 southern pine. Climatic data for the closest station were adjusted for any elevational differences using an average lapse rate of 5.46 °C per kilometer (Stone and Carlson, 1979) and then used to compute E_P. The model was run for each site, and a value of k was computed using equation (19). Table 6 summarizes the collected productivity values and the computed k values for each location.

The computed k values were then averaged for each vegetation type for use in future model runs. Final values were 0.36 for boreal, 0.66 for deciduous, and 0.31 for pine. They are in the appropriate range (Hargreaves (1966) gives maximum k values for orchard crops ranging from 0.55 to 0.75) and the comparative magnitudes of coniferous versus deciduous values are also as expected. Deciduous trees have a lower minimum stomatal resistance than coniferous trees, as well as a conducting system that is capable of higher rates of water transport (Larcher, 1983), therefore it is anticipated that the deciduous k should be larger than the coniferous k.

Table 6

Net Primary Productivity Data Used to Estimate k

Boreal Forest

Location	Latitude (°N)	elev. (m)	weather station	NPP	k	Source
Smoky Mtns., TN	35.53	1620	310300	920	0.49	Whittaker, 1966
Smoky Mtns., TN	35.53	1800	310300	980	0.56	Whittaker, 1966
Smoky Mtns., TN	35.53	1920	310300	465	0.28	Whittaker, 1966
Smoky Mtns., TN	35.53	1900	310300	650	0.39	Whittaker, 1966
Fairbanks, AK	64.82		502968	185	0.07	Miller, 1982
				Average:	0.36	

Deciduous Forest

Location	Latitude (°N)	elev. (m)	weather station	NPP	k	Source
Cedar Creek, MN	44.88		215435	707	0.38	Art & Marks, 1971
Cedar Creek, MN	44.88		215435	870	0.47	Reiners, 1972
Cedar Creek, MN	44.88		215435	762	0.41	Ovington et al., 1963
Hubbard Brook, NH	43.75	700	271683	848	0.74	Bormann & Likens, 1979
Smoky Mtns., TN	35.53	730	310300	1150	0.56	Whittaker, 1966
Smoky Mtns., TN	35.53	820	310300	1900	0.96	Whittaker, 1966
Smoky Mtns., TN	35.53	820	310300	1400	0.71	Whittaker, 1966
Smoky Mtns., TN	35.53	700	310300	2400	1.15	Whittaker, 1966
Smoky Mtns., TN	35.53	1310	310300	1050	0.67	Whittaker, 1966
Oak Ridge, TN	36.02	300	406750	1200	0.51	Whittaker, 1966
Oak Ridge, TN	36.02		406750	1526	0.64	Harris et al., 1975
Oak Ridge, TN	36.02		406750	1603	0.67	Harris et al., 1975
				Average:	0.66	

Southern Pine Forest

Location	Latitude (°N)	elev. (m)	weather station	NPP	k	Source
Bradford Cty., FL	29.67	45	082158	1326	0.36	Gholz & Fisher, 1982
Bradford Cty., FL	29.67	45	082158	1138	0.31	Gholz & Fisher, 1982
Bradford Cty., FL	29.67	45	082158	977	0.26	Gholz & Fisher, 1982
Bradford Cty., FL	29.67	45	082158	174	0.05	Gholz & Fisher, 1982
Bradford Cty., FL	29.67	45	082158	442	0.12	Gholz & Fisher, 1982
Bradford Cty., FL	29.67	45	082158	428	0.12	Gholz & Fisher, 1982
Bradford Cty., FL	29.67	45	082158	923	0.25	Gholz & Fisher, 1982
Bradford Cty., FL	29.67	45	082158	1296	0.35	Gholz & Fisher, 1982
Bradford Cty., FL	29.67	45	082158	1092	0.29	Gholz & Fisher, 1982
Smoky Mtns., TN	35.53	610	310300	820	0.32	Whittaker, 1963,1966
Smoky Mtns., TN	35.53	550	310300	950	0.36	Whittaker, 1963,1966
Aurora, NC	35.33	150	316108	1930	0.63	Nemeth, 1973
Aurora, NC	35.33	150	316108	1580	0.52	Nemeth, 1973
Triangle Res. Site, NC	36.00	135	317069	1152	0.40	Lieth, 1978
				Average:	0.31	

Chapter 6

Prediction of the Location of the Boreal Forest/Deciduous Forest Ecotone

The boreal forest–deciduous forest ecotone runs generally east–west (Figure 1) and has been empirically linked to various temperature constraints. Bryson (1966) correlates the winter position of the arctic front with the southern border of the boreal forest. Siccama (1974) found that the boreal/deciduous ecotone, which occurs at an elevation of 792 meters in the Green Mountains of Vermont, corresponds closely to the average height of clouds in the region. He attributes the change in vegetation to the increase in moisture resulting from the collection of water on and drip from needles in locations where clouds and fog are regular occurrences. He also found a pronounced decrease in the frost free period from 144 days in the area dominated by deciduous forest to only 92 days in the area dominated by boreal forest. Wolfe (1979) cites a mean annual temperature of 3° C as a worldwide predictor for the location of the boreal/deciduous ecotone, and Larsen (1980) compares the ecotone with the July 18° C average temperature isotherm.

There is a positive moisture balance (precipitation > evaporation) at most locations within the boreal forest formation and the mixed transition region (Mather, 1978), indicating that moisture is not likely to be the limiting factor influencing this boundary. Larsen (1980) and Ritchie (1987) concur that temperature is the most important factor determining boreal vegetation distribution. Based on this information, we chose to look first at temperature as the climatic variable responsible for determining the location of this ecotone.

6.1 Extreme Temperature Limitation of Deciduous Forest

One of the most direct effects of temperature on plants in the region of this boundary is the occurrence of below–freezing temperatures during several months of the year. The formation of ice within cells is generally lethal (Weiser, 1970; Burke et al., 1976), so plants have evolved various mechanisms which permit them to survive in environments where freezing occurs. These adaptations include insulation, freezing point depression, supercooling, extracellular and extraorgan freezing (Levitt, 1980; Sakai, 1979). Insulation is effective only for short time periods (a few hours) and freezing point depression is effective only to a maximum of –5 °C (Larcher, 1983). Since temperatures along the ecotone in question typically get much colder for much longer, these two adaptations will not be discussed here.

The primary methods of surviving freezing temperatures in temperate woody plants consist of deep supercooling, extracellular freezing, or extraorgan freezing (George, et al., 1974; Sakai, 1979). Deep supercooling consists of water in plant cells remaining in the liquid form at temperatures well below 0°C due to a lack of nucleation sites for ice crystal formation. As long as ice crystals do not form within the cell, it is not damaged. The lower limit for deep supercooling is the temperature at which homogeneous nucleation occurs, which is –40 °C for pure water. When plants which resist cold by supercooling are experimentally frozen, a low temperature exotherm (LTE), which indicates ice formation by detecting the release of latent heat (Weiser, 1970), can be measured in this temperature range. This condition of deep supercooling is stable to within one or two degrees of the homogenous nucleation temperature (George and Burke, 1977).

The temperature at which the freezing of supercooled water in cells begins varies among species of trees, within a single species, and even between the various organs of an individual plant (Weiser, 1970; Flint, 1972; Sakai and Weiser, 1973; Larcher, 1982; Sakai, 1982; Sakai, 1983). Deep supercooling to as low as –55° C has been reported in some plants (Gusta et al., 1983). These variations are due primarily to different concentrations of solutes in the cell sap which alter the homogeneous nucleation point. Once freezing of the deep supercooled water begins, it proceeds slowly over a range of 10 to 20 degrees, spreading from cell to cell within the plant (Hong and Sucoff, 1980). The amount of freezing damage that occurs will depend upon how long the temperature remains in the range at which freezing takes place. Whether or not the tree is killed or seriously injured will depend upon the location and extent of the damage (Hong et al., 1980; George et al., 1982).

The other two strategies, extracellular or extraorgan freezing, consist of the migration of water out of plant cells and/or organs such as buds into intercellular spaces. The intercellular spaces are large enough so that there is no physical damage as the water freezes and expands. This strategy permits plants to tolerate extremely low temperatures, limited only by the extent to which their cells can withstand the extreme dehydration caused by the removal of water (Sakai, 1979).

The results from several studies have shown that most species of trees native to the eastern deciduous forest of North America exhibit LTEs in their stems ranging from –41 °C to –55 °C, indicating that supercooling is the method of cold resistance used to protect the xylem tissue (George et al., 1974; Gusta et al., 1983). In most cases, injury or death of the twigs occurs within one or two degrees of the LTE and is thought to be the result of intracellular ice formation (Sakai and Weiser, 1973; George, et al., 1974; Gusta, et al., 1983). Sakai and Larcher (1987) suggest that certain types of xylem may be limited to supercooling as a freezing resistance method due to the lack of intercellular spaces for extracellular ice formation. Other tissues or organs within the same tree may resist cold through extracellular or extraorgan freezing and thus be hardy to lower temperatures (Sakai, 1978; Sakai and Larcher, 1987), however, the survival of the tree and thus its distribution will be limited by the least hardy overwintering tissue, which in this case is the xylem. Comparison of the northern range limit of each of these species with minimum temperature isotherms indicates that these species extend their range only as far north as the minimum temperature to which they can supercool (George, et al., 1974). This has led several authors to suggest that freezing injury may indeed be the limiting factor in the poleward distribution of these tree species (George et al., 1974; Marchand, 1987; Sakai and Larcher, 1987; Woodward, 1987).

In sharp contrast, those species which are native to the boreal forest of North America (primarily conifers, with some species of birch (*Betula*), willow (*Salix*) and poplar (*Populus*)) do not have LTEs in the –40 °C range (George, et al., 1974; Sakai, 1978). In experimental freezing, all of these species were uninjured at temperatures of –80 °C and below (Sakai and Weiser, 1973). This indicates that these species utilize extracellular or extraorgan freezing in their xylem as well as other tissues and are able to withstand the extreme dehydration that this process entails. Appendix A, Table 4 summarizes the freezing resistance for most tree species native to the boreal and deciduous forest formations. Care should be taken in interpreting these values, as tree origin and time of measurement can substantially affect freezing resistance (cf. Weiser, 1970; Flint, 1972; Sakai, 1973).

To test the hypothesis that supercooling as a method of freezing resistance may be responsible for the northern limit of the deciduous forest formation, we compared the observed boundary between the eastern deciduous forest and the boreal forest regions of North America (Eyre, 1968) with the observed –40 °C average annual minimum temperature isotherm (National Arboretum, 1960). Their close agreement (see Figure 12) indicates that supercooling as a means of resisting freezing stresses may

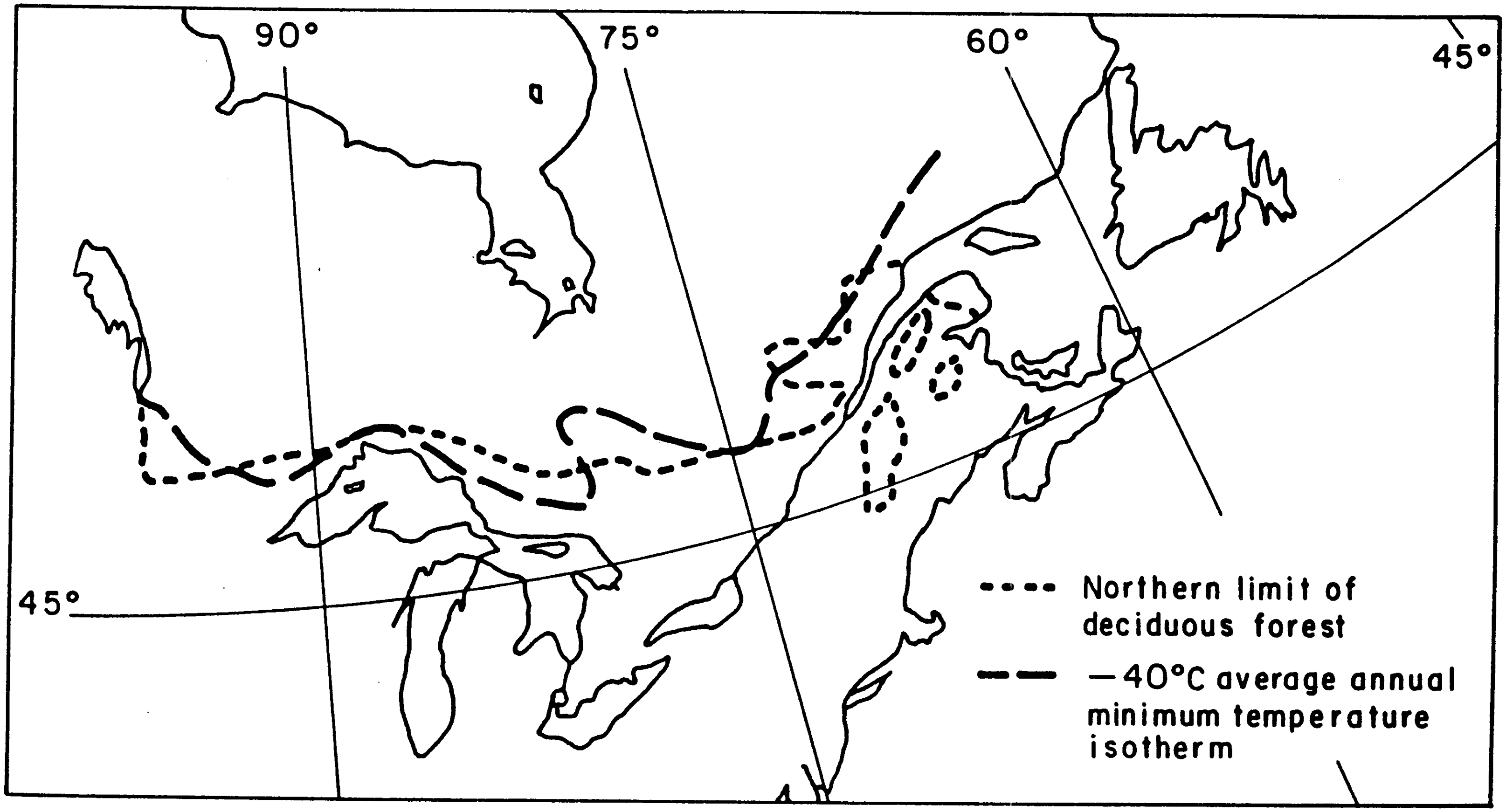

Figure 12: Comparison of the northern limit of deciduous forest (Eyre, 1968) with the −40 °C average annual minimum temperature isotherm (National Arboretum, 1960).

set an absolute physical limit for the northern migration of most deciduous trees, thereby determining the northern limit of the deciduous forest formation as well (Arris and Eagleson, 1989).

Although this mechanism may be adequate to explain the northern limit of the deciduous forest, it does not provide any insight into why the boreal forest does not grow at lower latitudes. To explore this, we used the productivity model discussed earlier.

6.2 The Boreal/Deciduous Ecotone as a Reversal in Competitive Advantage

As discussed previously, in the absence of absolute physical restrictions, such as the freezing resistance phenomenon, the location of ecotones is probably a function of the relative competitive abilities of the two vegetation types. In the case of the boreal–deciduous ecotone, our hypothesis is as follows:

In the warmer latitudes the deciduous trees have a relatively long growing season. The length of this growing season coupled with high photosynthetic rates leads to a higher net primary productivity for the deciduous trees compared with the conifers, because the lower photosynthetic rate of the conifers more than offsets their extended growing season due to their evergreen habit. As one progresses north, however, the growing season for the deciduous trees gets shorter and shorter, causing productivity to be reduced. The growing season for the conifers also gets shorter, but not as quickly. At some point, depending on relative photosynthetic rates and growing seasons, the conifers will become more productive than the deciduous trees because the high photosynthetic rates of the deciduous trees will no longer offset the greatly shortened growing season. Figure 13 illustrates the variation of primary production over the course of the year for these two vegetation types at a northern location (top)

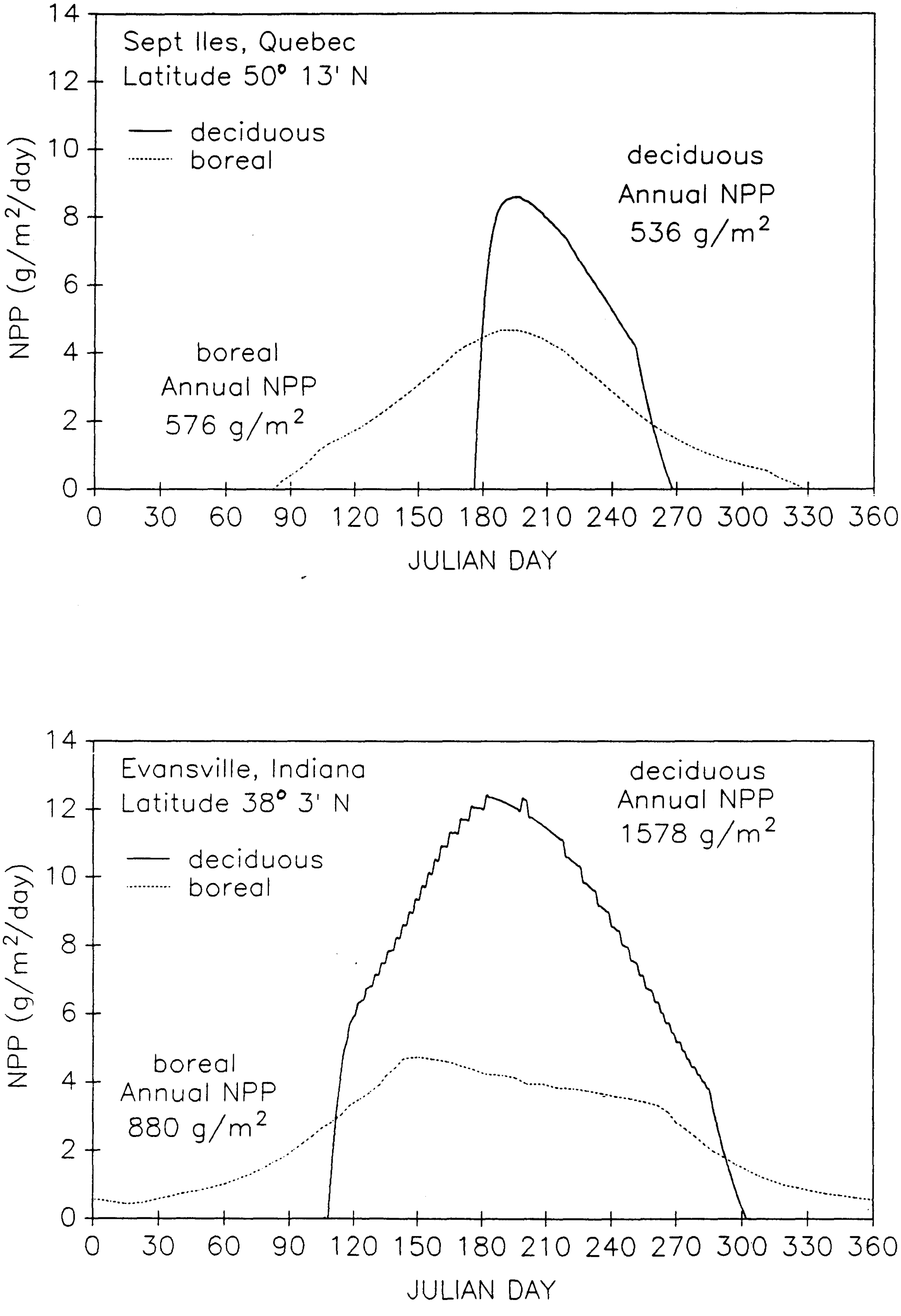

Figure 13: Comparison of the daily course of primary production in deciduous and boreal forests at a northern location (top) and a southern location (bottom).

and a southern location (bottom). The area under the curves represents the annual NPP, and the dominant type at each location has the greater productivity. If the hypothesis is valid, the latitude at which annual productivity for the two vegetation types is equal should mark the location of the ecotone.

Using the parameters discussed in Chapter 5, the model was run for the boreal and deciduous forest types and the productivities compared. Figure 14 illustrates the results. This figure indicates that the deciduous trees are indeed more competitive to a latitude of about 48 degrees north. The observed location of the ecotone as given by Eyre (1968) is indicated by the area between the two dotted lines. This reflects the latitude range of the mixed transition zone as shown in Figure 1. Some of the scatter in the data at each latitude is due to the range of longitudes over which the stations are spread.

As shown in figure 14, the ecotone as predicted by the model lies somewhat to the north of the observed ecotone. This indicates that the supercooling method of frost resistance is probably limiting the northward spread of the deciduous formation, whereas lack of competitive ability is restricting the boreal biome from moving further south. The presence of boreal species in the transition zone is probably due to topographic and other variability which leads to differences in microclimate. In this transition zone, a small reduction in temperature would be sufficient to shift the competitive advantage from deciduous forest to boreal forest. The sparsity of data stations in this region does not adequately reflect the variability of the microclimates of the area.

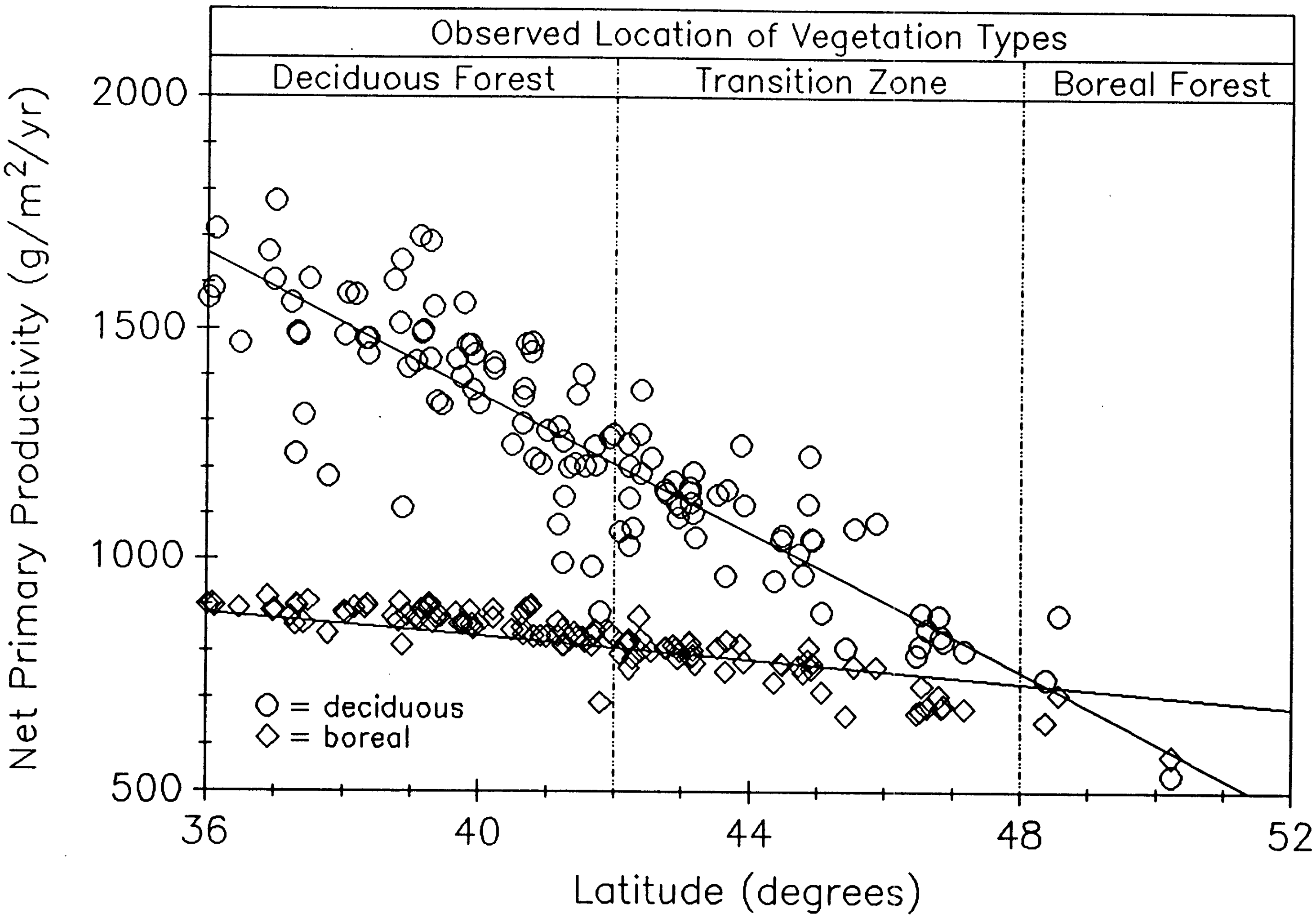

Figure 14: Annual net primary productivity versus latitude for deciduous and boreal forests in the eastern U.S.

Chapter 7

Prediction of the Location of the Deciduous Forest/Southern Pine Ecotone

For many years it was assumed that the pine forests of the coastal plain were a "fire subclimax" vegetation type that would revert to hardwoods in the absence of fire (Weaver and Clements, 1938). However, more recent investigations have revealed other possible reasons for the existence of the southern pine formation.

Hocker (1956) found that average temperature and the frequency and intensity of precipitation during the growing season were strongly correlated with the distribution of loblolly pine (*Pinus taeda*). Gleason and Cronquist (1964) and Eyre (1968), while citing fire as an important factor, also mention the sterile, sandy soils of the region as contributing to the dominance of pine. Croker (1969) subscribes to the fire subclimax theory as well, although he does point out that the soils are infertile, acid, and low in available water. Sakai and Weiser (1973) found that the four dominant southern pine species (see Chapter 3) were all susceptible to damage at temperatures below –10 °C, indicating that the pine may be temperature–limited in the north. Hicks and Chabot (1985) cite the long growing season, mild climate and infertile soils as factors favoring the growth of both pines and broad–leaved evergreens in the southern coastal plain. Christensen (1988) states that succession will lead to hardwoods on fertile, well–drained soils in this region but not on sandy soils due to a lack of nutrients.

7.1 Evidence for Water Limitations

Our initial hypothesis about the deciduous forest–southern pine ecotone was essentially the same as that for the boreal–deciduous ecotone except in reverse. The theory is that with increasingly warm winters at more southern latitudes the pines can photosynthesize essentially all year (Perry, 1971b), and that this should promote a higher net primary productivity than in the deciduous trees. However, as Figure 15 indicates, assuming an unlimited moisture supply, the pines do not have a higher productivity than the deciduous trees anywhere in their range, despite a longer growing season in the south. Clearly, some limiting factor other than the effects of temperature and growing season is operating at this boundary.

To assess the possibility of water limitation as a contributing factor to the

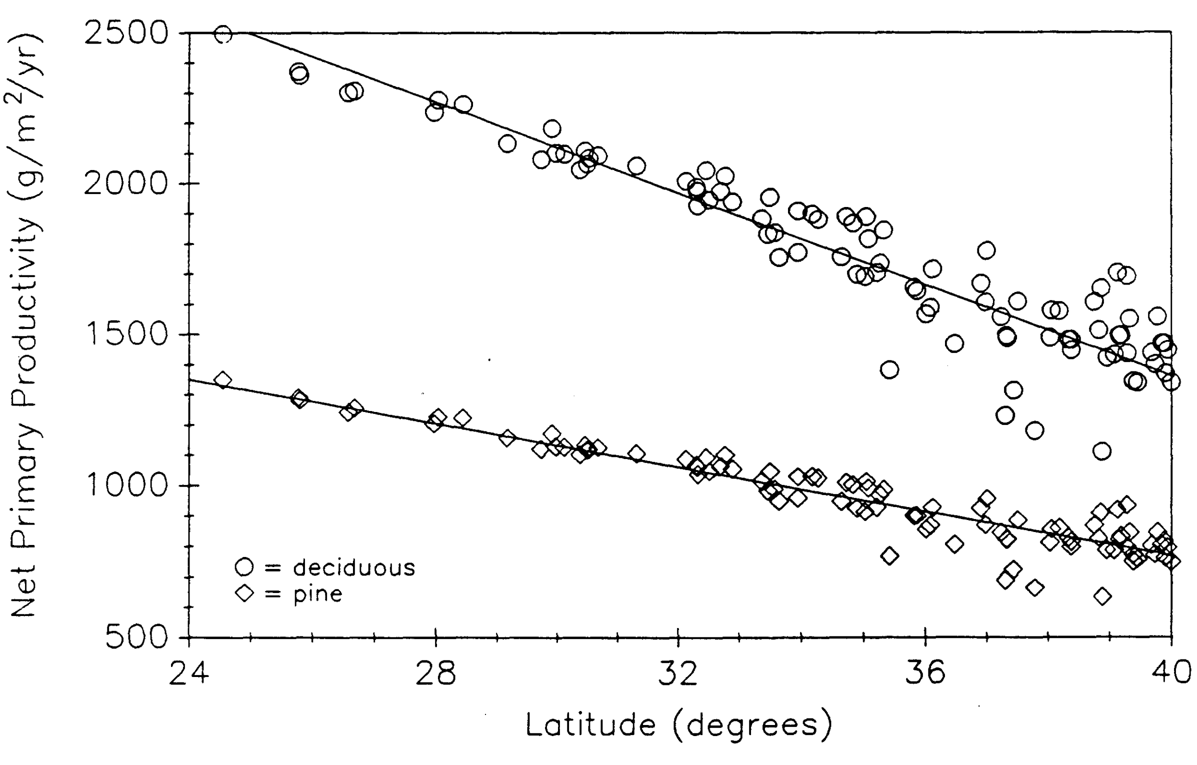

Figure 15: Annual net primary productivity for deciduous and pine forests assuming an unlimited moisture supply.

existence and location of this ecotone, it was necessary to incorporate information about precipitation, soil and vegetation characteristics into the productivity model.

7.2 Precipitation Characteristics

Interception and subsequent evaporation of precipitation on foliage, branches and litter may comprise a substantial amount of the total precipitation in forested areas (cf. Helvey and Patric, 1965). Interception is generally estimated using a formula of the form

$$\begin{aligned} I &= h && \text{for } h \le \tfrac{a}{1-b} \\ I &= a + bh^{n} && \text{for } h > \tfrac{a}{1-b} \end{aligned} \tag{20}$$

where I is the storm interception, h is total storm depth and a, b, and n are empirical coefficients (Wigham, 1970). These coefficients will vary with vegetation type owing to varying degrees of canopy cover and different foliage characteristics. Typically n is equal to one, leaving only the constants a and b to be estimated.

To incorporate interception relationships into the determination of the moisture balance of an area, gross precipitation must be reduced by the amount of intercepted rainfall. However, the interception equation uses total storm depth, whereas in the data set we are using the precipitation data consist of daily average values with no information provided about storm depths or durations. To transform the available data, we start first with the assumption that storm depths have a gamma distribution with parameters λ (cm^{-1}) and κ (dimensionless) (Eagleson, 1978a):

$$f_H(h) = G(\kappa,\lambda) = \frac{\lambda(\lambda h)^{\kappa-1}\, e^{-\lambda h}}{\Gamma(\kappa)} \tag{21}$$

Defining effective storm depth as

$$h_e = g(h) = h - I \tag{22}$$

where h_e is the net precipitation from a given storm actually available for infiltration or runoff, we have from combining (20) and (22)

$$\begin{aligned} h_e &= 0 && \text{for } h \leq \frac{a}{1-b} \\ h_e &= (1-b)h - a && \text{for } h > \frac{a}{1-b} \end{aligned} \tag{23}$$

We can find the expected value of h_e from the definition of expectation:

$$E[h_e] = E[g(h)] = \int_{-\infty}^{\infty} g(h)\, f_H(h)\, dh \tag{24}$$

Using (21), (22) and (23), equation (24) expands to

$$E[h_e] = \int_{0}^{a/1-b} 0\ f_H(h)\, dh + \int_{a/1-b}^{\infty} [(1-b)h-a]\, \frac{\lambda(\lambda h)^{\kappa-1} e^{-\lambda h}}{\Gamma(\kappa)}\, dh \tag{25}$$

with solution

$$E[h_e] = \frac{(1-b)}{\lambda(\kappa)}\, \Gamma\left[\kappa+1, \frac{\lambda a}{1-b}\right] - \frac{a}{\Gamma(\kappa)}\, \Gamma\left[\kappa, \frac{\lambda a}{1-b}\right] \tag{26}$$

We can also define the effective number of storms, n_{se}, by

$$\frac{n_{se}}{n_s} = \int_{a/1-b}^{\infty} f_H(h)\, dh = \frac{\Gamma\left[\kappa, \frac{\lambda a}{1-b}\right]}{\Gamma(\kappa)} \tag{27}$$

where n_s is the average number of storms in a season, as determined by

$$n_s = \frac{P_A}{E[h]} = \frac{P_A\,\lambda}{\kappa} \tag{28}$$

with

P_A = average annual precipitation (cm)

We can then represent the average annual *effective* precipitation as

$$P_e = n_{se}\, E[h_e] \tag{29}$$

Combining (26), (27), (28) and (29), we have

$$P_e = P_A \frac{\Gamma\left[\kappa, \frac{\lambda a}{1-b}\right]}{\kappa\ [\Gamma(\kappa)]^2} \left[(1-b)\, \Gamma\left[\kappa+1, \frac{\lambda a}{1-b}\right] - a\lambda\, \Gamma\left[\kappa, \frac{\lambda a}{1-b}\right]\right] \tag{30}$$

Use of this equation requires that P_A, a, b, κ and λ be known. P_A is obtained by summing over the entire year the daily average precipitation values obtained from the climatic data set described in Chapter 4.

Helvey and Patric (1965) summarized numerous interception studies on hardwoods in the eastern United States, and developed the following relationships:

$$\begin{aligned} I &= 0.091 + 0.211h && \text{during the growing season} \\ I &= 0.051 + 0.150h && \text{during the winter} \end{aligned} \tag{31}$$

for h and I in centimeters. This includes interception by leaves, stems and litter. Helvey (1971) did a similar review for conifers, which produced

$$I = 0.03 + 0.17h \tag{32}$$

for loblolly pine, with h and I in centimeters. This is, of course, valid year–round.

Eagleson and Tellers (1982) used water balance studies of several catchments in the eastern United States to estimate some of the necessary parameters for solving equation (30). Table 7 summarizes the precipitation characteristics they provide for two watersheds in the southeastern United States. Although the two watersheds are widely separated, the values for most of the important parameters are quite similar. Based on this, we are assuming that these parameters can be applied to the southeastern U.S. in general.

Table 7

Precipitation Parameters for Two Catchments in the Southeastern U.S.

Parameter	Chattahoochee (West Point, GA)	James (Cartersville, VA)	Value Used in Model
m_τ (days)	365	365	365
m_{tb} (days)	3.82	3.87	3.845
m_{tr} (days)	0.32	0.21	0.265
κ	0.60	0.53	0.56

Although λ is not explicitly given in this paper, we can compute it from the available information. We can represent the number of storms, n_s, as

$$n_s = \frac{m_\tau}{(m_{tr} + m_{tb})} \tag{33}$$

where

m_τ = average length of the rainy season (days)
m_{tr} = average storm duration (days)
m_{tb} = average time between storms (days)

Values for these parameters are given in Table 7. Combining (28) and (33), we have

$$\lambda = \frac{m_\tau \kappa}{(m_{tr} + m_{tb})\ P_A} \tag{34}$$

where the units of λ are the inverse of those of P_A.

Since the rainy season is 365 days long at these locations, these parameters should be appropriate for use on a seasonal as well as an annual basis. By simply substituting seasonal average precipitation for annual average precipitation in equation (30), we can compute seasonal effective precipitation.

7.3 Seasonal Moisture Balance

One theory that has been proposed for the existence of the coniferous forests of the Pacific Northwest is a modification of the productivity/competition hypothesis discussed earlier. In the Pacific Northwest, most of the annual precipitation is received during the winter when only the conifers can take advantage of it. During the summer, when the deciduous trees must accomplish all of their yearly carbon fixation, the precipitation is low and significant water stress occurs. This stress reduces photosynthetic rates in both types of trees. However, because of the mild winters of the region, the conifers can make up for this reduction during the winter. This gives them a competitive advantage over the deciduous trees and therefore they dominate in that region (Waring and Franklin, 1979).

To test whether the idea of a seasonal moisture deficit might be applicable to the situation in the southeastern U.S., we compared seasonal effective precipitation with seasonal evapotranspiration for each vegetation type. We defined the season as the deciduous growing season and computed runoff as the difference between precipitation and evapotranspiration. A negative result indicates a seasonal moisture deficit. The results, computed for each climatic data station between 24 and 38 °N latitude, are shown in Figure 16.

It is interesting to note that the trend here appears to be the reverse of the northwestern situation. In the south, the regions dominated by pine have a summer moisture surplus whereas in the region dominated by hardwoods there is a summer deficit, which is exactly the opposite of what would be anticipated if seasonal moisture deficits were responsible for this ecotone. This illustrates the necessity of including the effect of moisture availability from the soil when analyzing this ecotone.

7.4 Soil Characteristics

As mentioned at the beginning of this chapter, soils are often cited as an important reason for the dominance of pine in the southern coastal plain. Oak–pine communities are also found on sandy soils along the Atlantic coast as far north as Cape

Cod (Kuchler, 1964), and pine communities are found on sandy soils throughout the deciduous forest formation (Spurr and Barnes, 1980). A further indication that soils may be a factor controlling this ecotone comes from a review of the vegetation history of eastern North America for the past 40,000 years, derived from the analysis of fossil pollen (Delcourt and Delcourt, 1981). This analysis indicates that the southern pine forest was located in essentially the same area as it is today, even though all other vegetation types shifted considerably, presumably due to the lower temperatures of glacial time periods. Figure 17 is a map of the reconstructed distribution of vegetation at the height of the last glaciation (18,000 BP) (Delcourt and Delcourt, 1979), which clearly illustrates the similarity of the location of the pine formation to that of the present day.

To analyze the possibility that soil characteristics may be a factor in

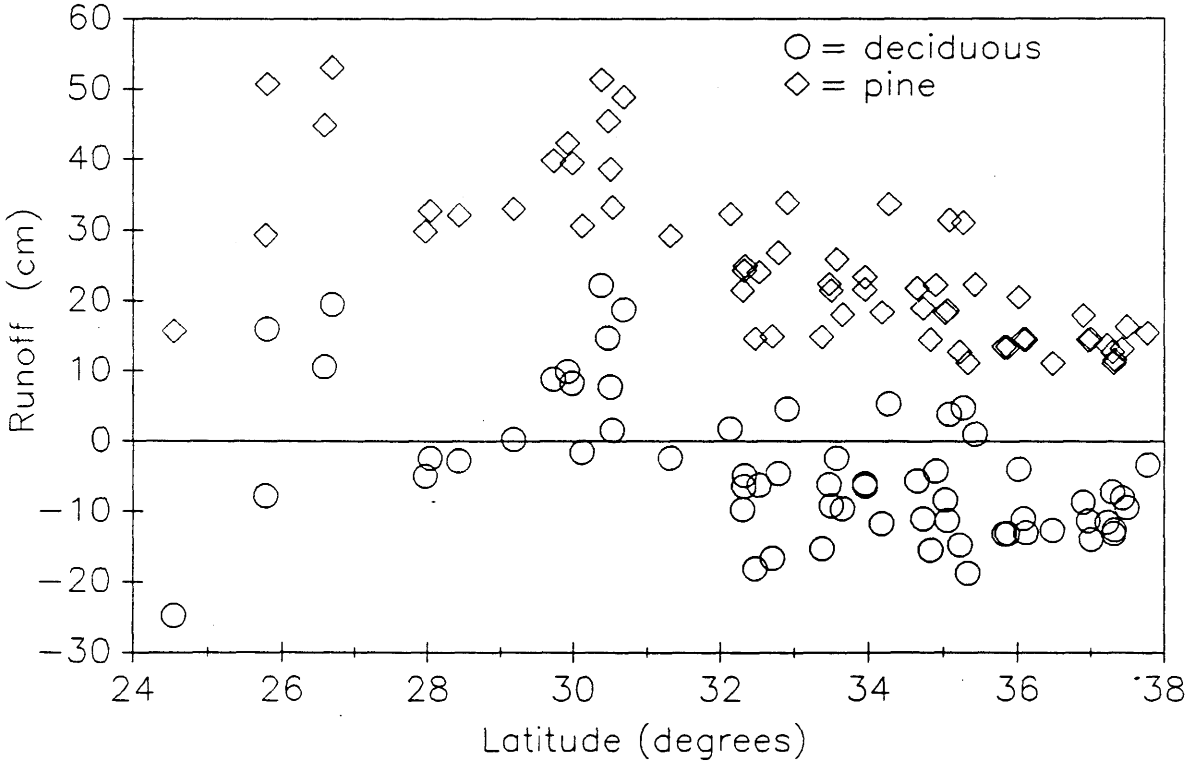

Figure 16: Seasonal water balance of the southeastern United States computed for the deciduous growing season.

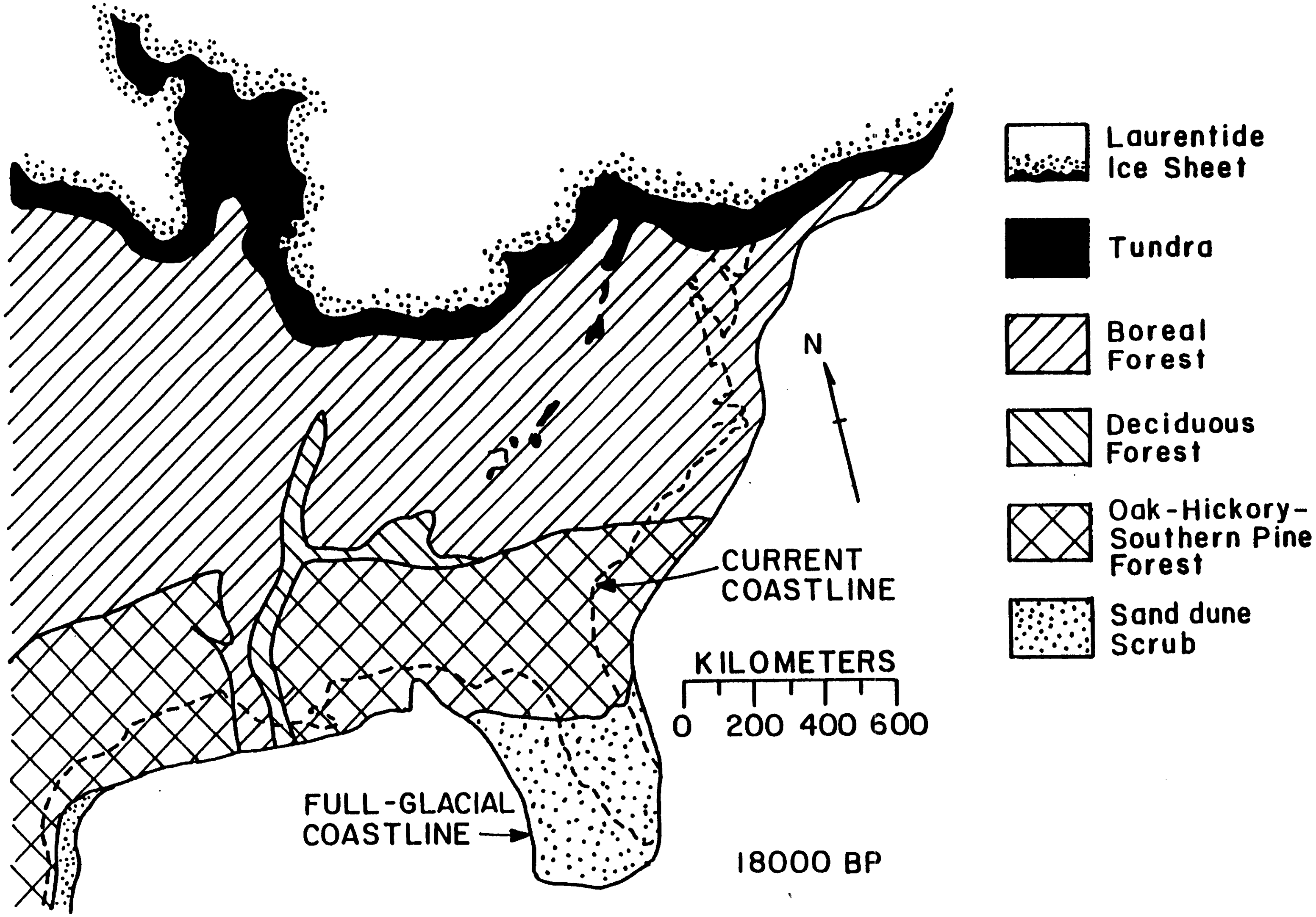

Figure 17: Full–glacial distribution of vegetation (18,000 BP) (redrawn from Delcourt and Delcourt, 1979).

determining the location of the deciduous–southern pine ecotone, we first collected information about southern soils. To accomplish this, two transects were laid out along longitudes of 82° and 86° W. We then "sampled" every 30 minutes of latitude from 37° to 26.5° N along the 82° transect and from 37° to 30.5° N along the 86° transect. Sampling consisted of obtaining a soil survey for the county located at each point (Soil Conservation Service, County Soil Surveys), and selecting the most abundant soil type in that county as a representative soil. Table 5 in Appendix A summarizes the transects and lists the counties, states, whether or not surveys were available, and the soil type chosen for the counties that were available.

Quantitative information collected for each soil type included depth, saturated hydraulic conductivity, and available water capacity for each layer of soil. Table 6 in Appendix A summarizes these values for each of the soil types. Average conductivity and available water capacity values were generated by weighting the value for each layer by the depth of that layer. Summaries of the weighted averages are shown in Table 8. We then plotted average conductivity and available water capacity as a function of latitude (Figures 18 and 19), and both showed a significant relationship. Conductivity increases and available water capacity decreases as one moves south, indicating that the soils are becoming sandier.

We reasoned that even if precipitation is adequate to account for evaporation, if the soil is very sandy, this moisture may percolate rapidly to the water table and then be unavailable to the plants. Eagleson (1978b, 1978d) has developed a methodology for estimating the long term average soil moisture in the surface boundary layer from climatic data and soil properties. We adapt that here to estimate the average soil moisture during the growing season, assuming as a first approximation that the climate year–round is that of the growing season in terms of precipitation and evaporation.

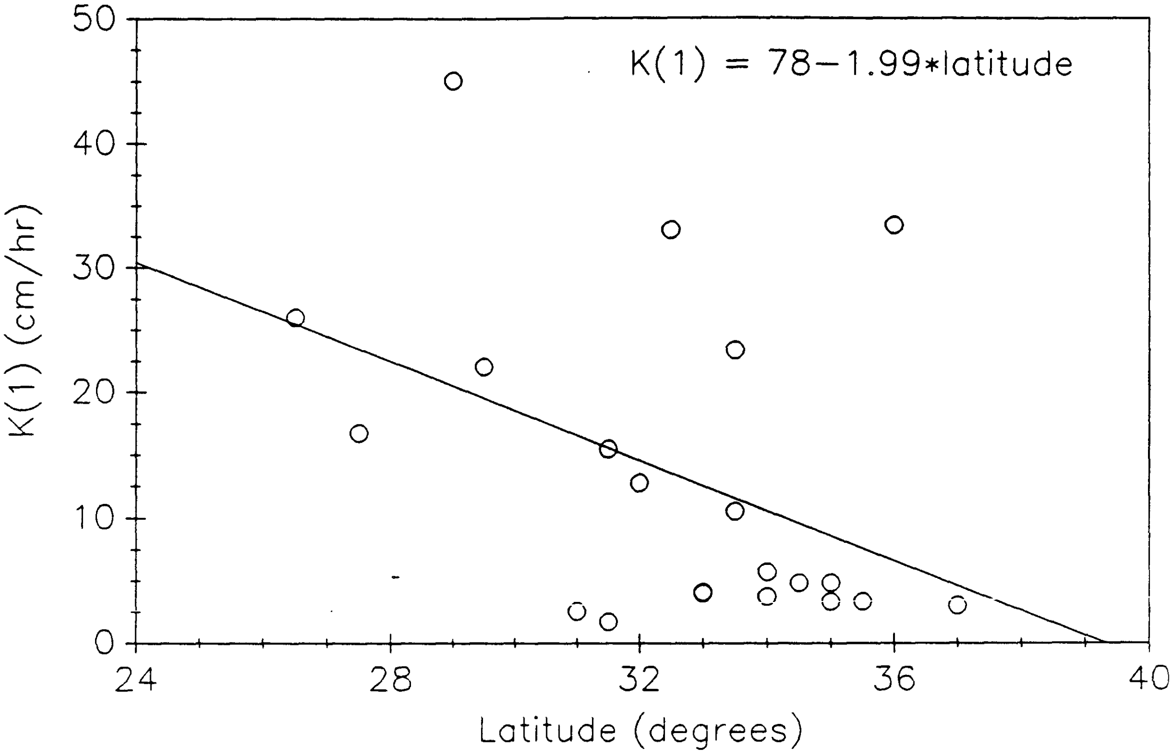

Figure 18: Saturated hydraulic conductivity versus latitude from soil survey data.

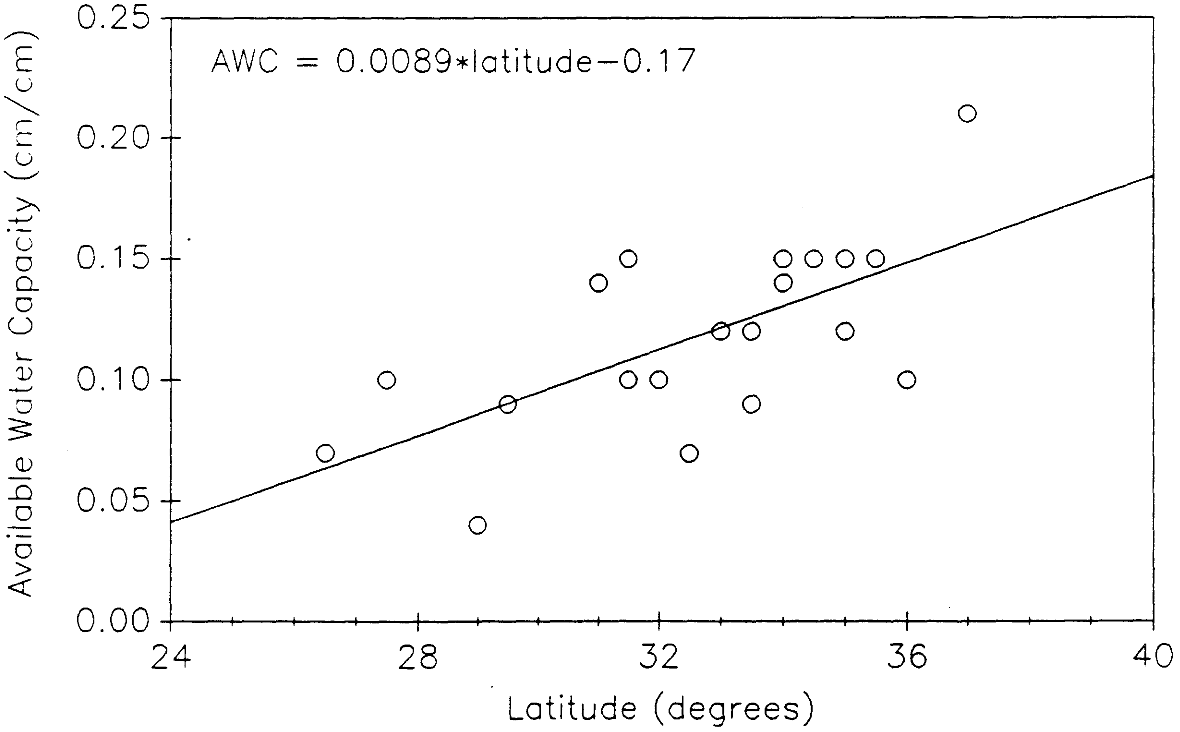

Figure 19: Available water capacity versus latitude from soil survey data

Table 8

Properties of Southeastern Soils

Soil Type	Latitude (degrees)	Saturated hydraulic conductivity (cm hr^{-1})	available water capacity (cm)	soil depth (cm)
82° transect				
Cecil Sandy Loam	35.0	3.35	0.30	183
Cecil Sandy Loam	34.0	3.76	0.36	196
Troup Fine Sand	33.5	23.37	0.23	203
Dothan Loamy Sand	33.0	4.11	0.30	157
Osier	32.5	33.02	0.18	157
Pelham/Tifton Loamy Sands	32.0	12.78	0.25	170
Plummer Soil/Rutledge Sand	31.5	15.47	0.25	127
Troup/Pomona/Immokalee Fine Sands	29.5	22.02	0.23	203
Candler Sand	29.0	45.06	0.10	251
Pomona Fine Sand	27.5	16.76	0.25	203
Immokalee Fine Sand	26.5	25.96	0.18	203
86° transect				
Baxter Cherty Silt Loam	37.0	3.02	0.53	132
Bodine Cherty Silt Loam	36.0	33.40	0.25	201
Mountview Silt Loam	35.5	3.35	0.38	152
Hartsells Fine Sandy Loam	35.0	4.88	0.38	91
Hartsells Fine Sandy Loam	34.5	4.88	0.38	91
Hartsells Fine Sandy Loam	34.0	5.74	0.38	79
Louisa Slaty Loam	33.5	10.54	0.30	61
Cecil Gravelly Sandy Loam	33.0	4.04	0.30	157
Luverne	31.5	1.73	0.38	165
Dothan Sandy Loam	31.0	2.57	0.36	165

Neglecting capillary rise from the water table and assuming a completely vegetated surface with no surface runoff, the long–term average soil moisture relationship for the growing season is

$$\text{Precipitation} = \text{Evapotranspiration} + \text{Deep Percolation} \tag{35a}$$

or

$$\overline{P}_{gs} = \overline{E}_{T_{gs}} + K(1)s_\theta{}^c \tag{35b}$$

Rearranging,

$$s_0 = \left[\frac{\overline{P}_{gs} - \overline{E}_{T_{gs}}}{K(1)} \right]^{1/c} \tag{36}$$

where

s_0 = time average soil moisture (dimensionless) ($0 \leq s_0 \leq 1$)

$\overline{P}_{gs}$ = average growing season precipitation (cm day^{-1})

$\overline{E}_{T_{gs}}$ = average growing season evapotranspiration (cm day^{-1})

K(1) = saturated hydraulic conductivity (cm day^{-1})

c = pore disconnectedness index (dimensionless)

It should be noted here that s_0 as derived by Eagleson (1978b) is *effective* soil moisture, which is defined as

$$s_e = \frac{\theta - \theta_r}{n - \theta_r} \tag{37}$$

where

s_e = effective soil moisture (dimensionless)
θ = volumetric soil moisture content (cm^3 H$_2$0 cm^{-3} soil)
θ_r = residual soil moisture content (cm^3 H$_2$0 cm^{-3} soil)
n = porosity (cm^3 voids cm^{-3} total soil volume)

Residual soil moisture, θ_r, is defined as the soil water content at which further reductions in soil water potential (ψ as defined in chapter 4) have no effect on soil moisture content ($d\theta/d\psi = 0$) (Van Genuchten, 1980). This definition of effective soil moisture leads to a comparable definition of effective porosity,

$$n_e = n - \theta_r \tag{38}$$

where n_e is effective porosity and n and θ_r are as previously defined. All of the following derivations and calculations use effective porosity and effective soil moisture unless otherwise specified.

$\overline{P}_{gs}$ is computed using equation (30) with total seasonal precipitation taking the place of total annual precipitation, and the resultant P_e is divided by the growing season length. The average growing season evapotranspiration $\overline{E}_{T_{gs}}$ can be computed directly from the productivity model as

$$\overline{E}_{T_{gs}} = \frac{k \sum_{\tau} C\ L\ E_P}{\tau} \tag{39}$$

where τ is the growing season and all other parameters are as described in chapter 5. With the exception of the very beginning and very end of the growing season, C and L will be equal to one, therefore equation (39) can be rewritten as

$$\overline{E}_{T_{gs}} \cong \frac{k \sum_{\tau} E_P}{\tau} \tag{40}$$

The relationship of saturated hydraulic conductivity to latitude developed previously (Figure 18) produced the following equation:

$$K(1) = 78 - 1.99\phi, \qquad R^2 = 0.43 \tag{41}$$

where K(1) is in centimeters per hour and ϕ is latitude in degrees. This relationship is only valid between latitudes 24 and 38° N.

The pore disconnectedness index, c, is a parameter developed by Brooks and Corey (1964) to describe relationships between soil moisture content and water potential. Experimentally derived values of c range from less than 4 for some sands to 18 for clay soils (Brooks and Corey, 1964; Rawls et al., 1982), and the theoretical lower limit is $c > 3.0$ (Brooks and Corey, 1964). However, Eagleson and Tellers (1982) fit values of c to long–term water yield data for six different watersheds in the United States and found that all values fell within the range $4.74 \leq c \leq 5.50$. As a first approximation, therefore, we chose a value of 5 for c.

Upon analysis of equations (35) and (36), we decided to include off–season precipitation and evaporation in the calculation of s_0, because there is a storage component which carries over from the dormant season to the growing season. We can redefine s_0 as

$$s_0 = \left[\frac{\overline{P}_{gs} + \overline{P}_{ds} + \overline{E}_{T_{gs}} + \overline{E}_{T_{ds}}}{K(1)}\right] \tag{42}$$

where

$\overline{P}_{ds}$ = average dormant season precipitation (cm day^{-1})

$\overline{E}_{T_{ds}}$ = average dormant season evapotranspiration (cm day^{-1})

and all other terms are as previously defined. The definition of dormant season precludes the possibility of transpiration, as there are either no leaves (deciduous) or the trees are inactive due to temperature restrictions (pine). There is, however, a definite possibility of evaporation from the ground surface especially in the deciduous case since the leaves are off the trees and the underbrush. There are then two possible extremes for dormant season evapotranspiration.

The first possibility is that no evaporation occurs due to litter cover, snow cover, and/or cool temperatures. To analyze this extreme, $\overline{P}_{gs}$, $\overline{P}_{ds}$, and $\overline{E}_{T_{gs}}$ were determined from the climatic data set using the relationships in equations (30), (31), (32) and (40) for each station between 24 and 38 °N latitude, and these values were used to compute s_0 using equation (42), keeping $\overline{E}_{T_{gs}}$ equal to zero. The results are shown in Figure 20. Despite the fact that the pines are transpiring essentially year–round, the deciduous trees still have a lower long–term average soil moisture concentration. This indicates that they will experience water stress prior to the pines regardless of whether or not evaporation occurs during the dormant season.

The other extreme is that where evaporation takes place during the dormant season at a rate similar to that from bare soil, limited only by available moisture. Eagleson (1978c) has a defined a parameter he terms evaporation effectiveness (E), which represents the ratio of actual evaporation from bare soil to potential evapotranspiration as a function of soil moisture. The asymptotes to this are

$$\frac{\overline{E}_{T_{ds}}}{\overline{E}_{P_{ds}}} = \left[\frac{\pi E}{2}\right]^{1/2} \qquad \text{for } E < \frac{2}{\pi}$$

$$\frac{\overline{E}_{T_{ds}}}{\overline{E}_{P_{ds}}} = 1 \qquad \text{for } E \geq \frac{2}{\pi} \tag{43}$$

where $\overline{E}_{T_{ds}}$ and $\overline{E}_{P_{ds}}$ are average actual and potential evapotranspiration, respectively, for the dormant season (cm day^{-1}), and E is defined as

$$E = \frac{2\ \beta\ n_e\ K(1)\ \psi(1)}{\pi\ m\ \overline{E}^2_{P_{ds}}}\ \phi_e\ s_0^{d+2} \tag{44}$$

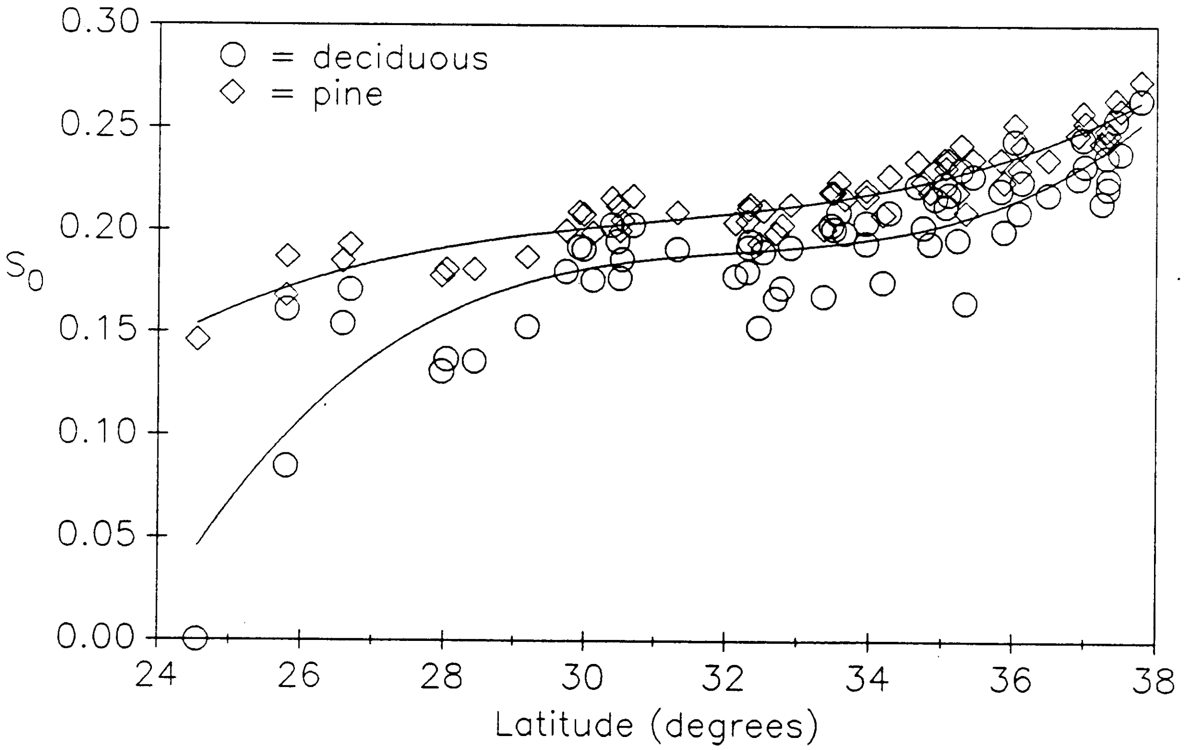

Figure 20: S_0 computed neglecting dormant season evapotranspiration

in which

β = reciprocal of the average time between storms (days^{-1})
n_e = effective porosity (dimensionless)
$K(1)$ = saturated hydraulic conductivity (cm day^{-1})
$\psi(1)$ = saturated soil moisture potential (cm suction)
m = pore size distribution index (dimensionless)
$\overline{E}_{P_{ds}}$ = average dormant season potential evapotranspiration (cm day^{-1})
ϕ_e = exfiltration diffusivity (dimensionless)
s_0 = annual average soil moisture concentration (dimensionless)
d = diffusivity index (dimensionless)

Each of these parameters is derived and discussed by Eagleson (1978b). Several of them have been defined previously in this chapter. A brief overview of the remainder follows.

The saturated soil moisture potential is actually the air breakthrough "bubbling pressure" of a saturated sample when drained by applied suction. It is computed as

$$\psi(1) = \frac{\sigma_w}{\gamma_w}\left[\frac{n_e}{k(1)\ \Phi}\right]^{1/2} \qquad (45)$$

where

σ_w = surface tension of pore water (N cm^{-1})
γ_w = specific weight of water (N cm^{-3})
$k(1)$ = saturated effective intrinsic permeability (cm^2)
Φ = pore shape parameter (dimensionless)

and n_e is as previously defined. The saturated effective intrinsic permeability is defined as

$$k(1) = \frac{\mu_w}{\gamma_w} K(1) \tag{46}$$

where μ_w is the dynamic viscosity of water (N–s cm^{-2}) and all other terms are as previously defined. The pore shape parameter can be estimated from

$$\Phi = 10^{0.66+0.55/m+0.14/m^2} \tag{47}$$

where

$$m = \frac{2}{c-3} \tag{48}$$

with c as previously defined. Finally, for integer values of d, the exfiltration diffusivity can be calculated as

$$\phi_e = 1 + 1.85 \sum_{n=1}^{d} \frac{(-1)^n}{1.85 + n} \begin{bmatrix} d \\ n \end{bmatrix} \tag{49}$$

where

$$d = \frac{c + 1}{2} \tag{50}$$

Many of these values can be represented as constants for the purposes of this model. The values we used are summarized in Table 9.

The solution of equation (42) must now be carried out iteratively. As before, $\overline{P}_{gs}$, $\overline{P}_{ds}$, and $\overline{E}_{T_{gs}}$ were determined from the climatic data set using the relationships in equations (30), (31), (32) and (40) for each station between 24 and 38° N latitude.

K(1) was determined using equation (41). Initially, s_0 is set to zero, which produces a zero value for E and thus a zero value for $\overline{E}_{T_{ds}}$. Equation (42) is then solved for s_0 and this value of s_0 is used to compute E from equation (44). A new value of $\overline{E}_{T_{ds}}$ is then computed using equation 43, and the process is repeated until successive values of s_0 differ by less than 0.0009. Figure 21 shows the results of these computations.

When Figure 21 is compared with Figure 20, we see that including dormant season evaporation makes a significant difference in the value of s_0 for deciduous forests. The zero values represent a negative numerator in equation (42). Due to the mild winters in this area, it is likely that dormant season evaporation will approach this limit, therefore we haven chosen this as our model for computing s_0.

To assess how these s_0 values may be affecting the vegetation of the region, the relationship between soil moisture content (s_e) and soil water potential (ψ) must be quantified (see chapter 4). This relationship is of critical importance in determining how changes in soil moisture are likely to affect plant physiological processes. Unfortunately, there is a great deal of variability in the methods used by different authors to characterize this relationship. Some examples follow.

The Brooks and Corey model (1964) used in the above analysis incorporates the

Table 9

Parameters used to Compute E

Parameter	Value	units	reference
c	5.0	–	see text
β	0.26	days^{-1}	see table 7
σ_w	7.4×10^{-4} (10 °C)	N cm^{-1}	physical tables
γ_w	9.8×10^{-3} (10 °C)	N cm^{-3}	physical tables
μ_w	1.3×10^{-7} (10 °C)	N–s cm^{-2}	physical tables
m	1.0	–	equation (48)
Φ	22.4	–	equation (47)
d	3.0	–	equation (50)
ϕ_e	0.11	–	equation (49)
n_e	0.40	–	Rawls et al., 1982

following definition:

$$s_e = \left[\frac{\psi(1)}{\psi} \right]^m \tag{51}$$

where all terms are as previously defined. Rawls et al. (1982) summarized experimental data for a large number of soils and presented average values of n, θ_r, n_e, $\psi(1)$, m and K(1) for all the USDA soil texture classes Figure 22 shows the relationship between K(1) and m and Figure 23 shows the relationship between K(1) and $\psi(1)$ plotted from these data. Linear regression analysis of the data provides the following equations:

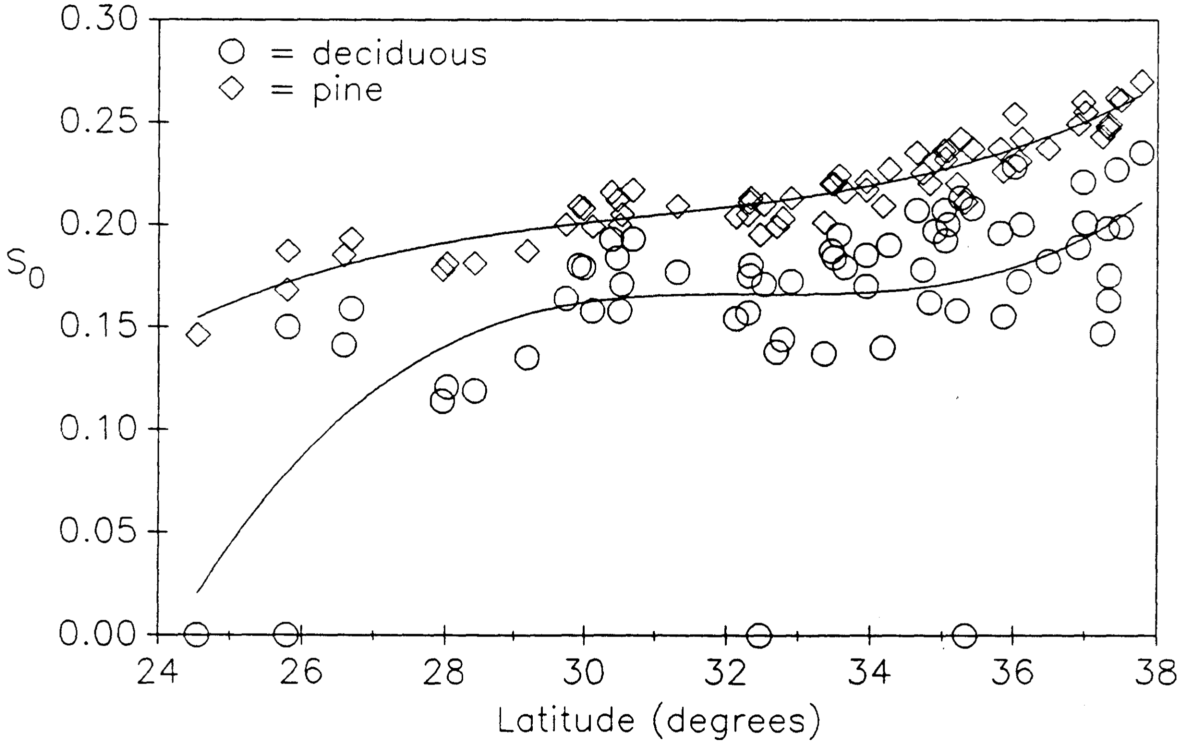

Figure 21: S_0 computed including dormant season evaporation.

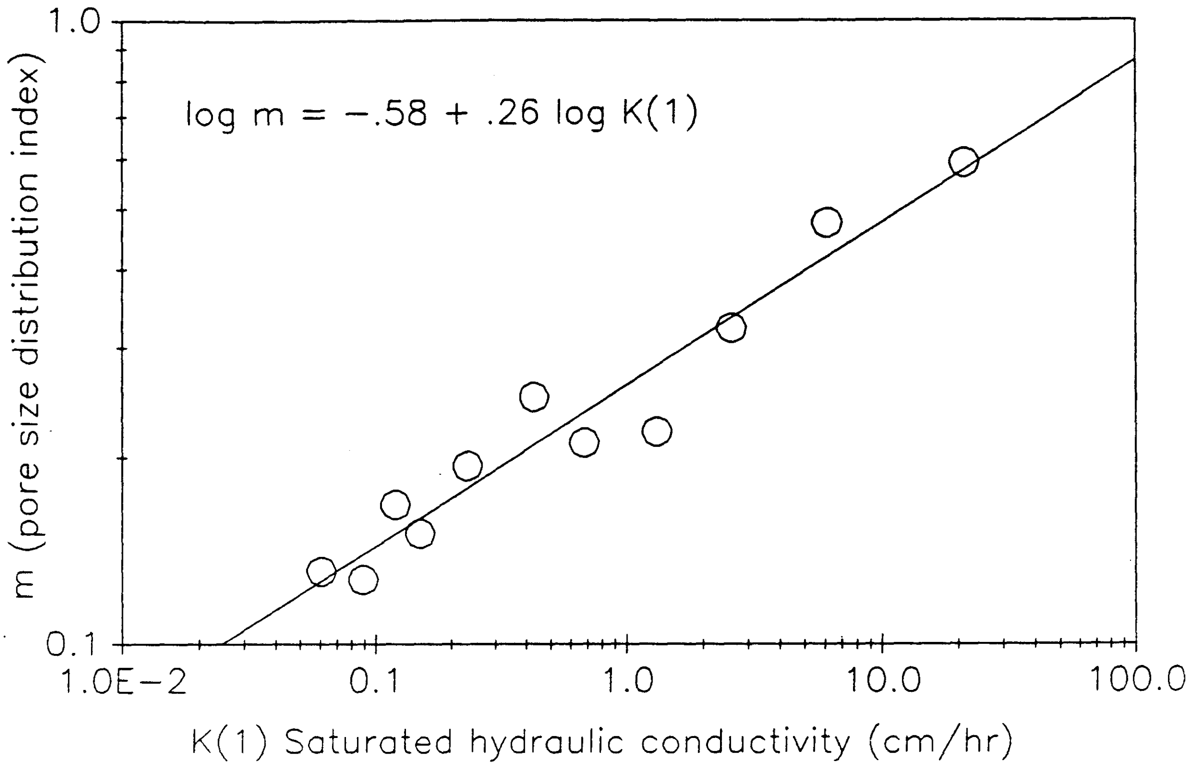

Figure 22: m versus K(1) (data from Rawls, 1982).

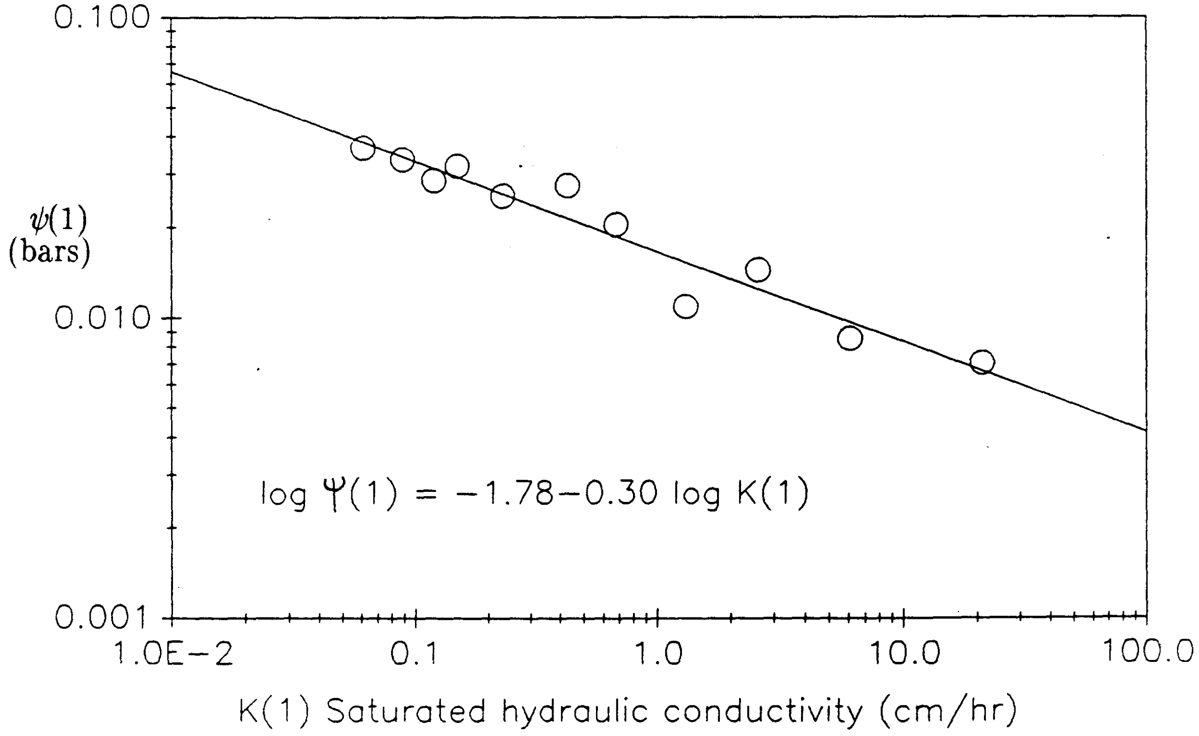

Figure 23: $\psi(1)$ versus K(1) (data from Rawls, 1982).

$$\log m = -0.58 + 0.26 \log K(1) \qquad (52)$$

and

$$\log \psi(1) = -1.78 - 0.30 \log K(1) \qquad (53)$$

In both of these equations , K(1) is in cm hr^{-1}, and in (53), $\psi(1)$ is in bars.

Combining these relationships with the relationship of K(1) and latitude given in equation (41) and using this information in equation (51), curves 1 and 2 in Figure 24 were computed for latitudes 24 and 38° N, respectively.

Milly and Eagleson (1982) adapted a model from Mualem (1977) to obtain the following:

$$s_e = \frac{\theta_d(\psi)}{n_e} \qquad (54)$$

where

$$\theta_d(\psi) = 2 - \frac{\theta_w(\psi)}{\theta_u}\,\theta_w(\psi) \qquad (55)$$

and

$$\theta_w(\psi) = \min\ \{\ \theta_u,\ Q(\psi/B)^V + D[\ 7 - \log(-\psi)] + G\} \qquad (56)$$

where θ_u is the proportion of soil occupied by water after rewetting (less than porosity due to air entrapment), ψ is in cm, and Q, B, V, D and G are empirical constants. Milly and Eagleson (1982) fitted parameters for this relationship to a sand and a silt

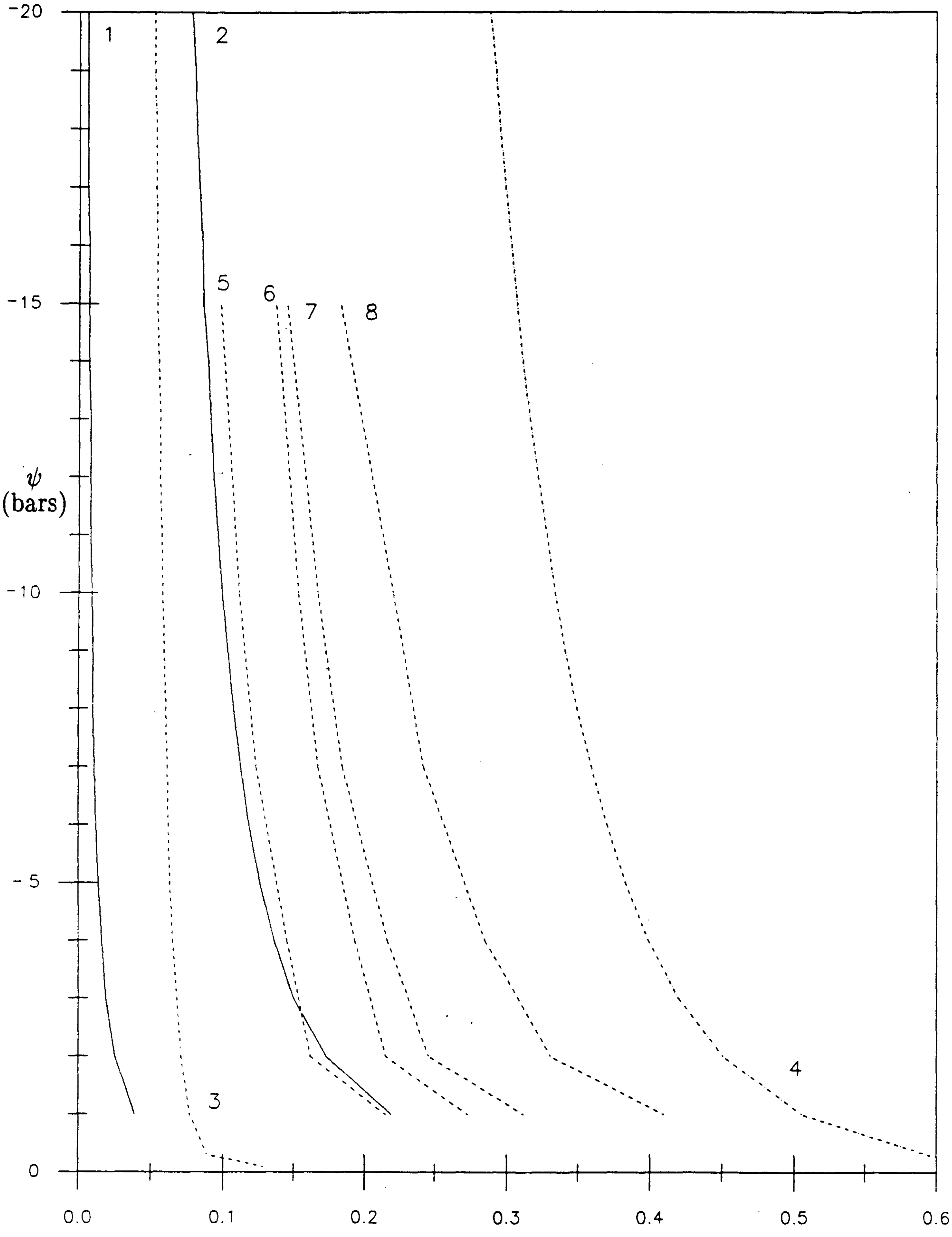

Figure 24: Comparison of s–ψ relationships developed by various authors (Brooks and Corey, 1964; Milly and Eagleson, 1982; Rawls et al., 1982).

loam (Table 10), and the results are shown as curves 3 and 4 in figure 24. It should be noted that they assume $\theta_r = 0$; therefore $n = n_e$ and $s = s_e$.

Rawls et al. (1982) developed linear regression equations for θ at specific values of ψ, which can then be converted to s_e using equation (37). These equations take the form

$$\theta = f + g(\%\text{sand}) + u(\%\text{silt}) + i(\%\text{sand}) + j\,(\%\text{organic matter}) \tag{57}$$

where

$$\%\text{sand} + \%\text{silt} + \%\text{clay} = 100 \tag{58}$$

The values for the coefficients at specific ψ values are summarized in Table 11. The original coefficients for the –15 bar ψ equation produced s_e values that were higher than those at –10 bars, so they have been adjusted to produce more reasonable values. Using these coefficients, equation (37) and the data in Table 12, curves 5 through 8 in Figure 24 were computed. Curves 5 and 6 are sands, curve 7 is a loamy sand and curve

Table 10

Fitted Parameters for Mualem Model

	Curve	
Parameter	3	4
soil type	sand	silt loam
$K(1)$ (cm hr^{-1})	7.2	0.36
n	0.35	0.46
θ_u	0.315	0.414
Q	0.171	0.210
B	–15.7	–495.0
V	–1.77	–0.147
D	0.00343	0.0
G	0.0	–0.0489

Table 11

Regression Coefficients for Rawls et al. (1982) Model

ψ (bars)	Coefficient				
	f	g	u	i	j
−1	0.0349	0	0.0014	0.0055	0.0251
−2	0.0281	0	0.0011	0.0054	0.0200
−4	0.0238	0	0.0008	0.0052	0.0190
−7	0.0216	0	0.0006	0.0050	0.0167
−10	0.0205	0	0.0005	0.0049	0.0154
−15	0.0260	-1.23×10^{-4}	0	0.0050	0.0158

Table 12

Soil Particle Size Distributions

	Curve Number				
Parameter	5	6	7	8	Source
soil type	sand	sand	sandy loam	loamy sand	
%sand	100	92	82	58	Cosby et al., 1984
%silt	0	5	12	32	Cosby et al., 1984
%clay	0	3	6	10	Cosby et al., 1984
%organic matter	3	3	3	3	Brady, 1974
θ_r	0.020	0.020	0.035	0.041	Rawls et al., 1982
n_e	0.420	0.417	0.401	0.412	Rawls et al., 1982

Table 13

Comparison of s values from different models

Curve	Soil type	K(1) (cm hr^{-1})	s at ψ=−1 bar	s at ψ=−15 bars
1	sand	30.61	0.039	0.007
2	sandy loam	2.87	0.219	0.086
3	sand	7.20	0.077	0.071
4	silt loam	0.036	0.506	0.451
5	sand	30.61 (est.)	0.215	0.098
6	sand	21.00	0.273	0.137
7	loamy sand	6.11	0.312	0.145
8	sandy loam	2.59	0.410	0.183

8 is a sandy loam.

It is readily apparent from Figure 24 that models of the relationship between s_e and ψ, while similar in shape, vary greatly in magnitude for similar soil types! Table 13 summarizes values of K(1) and values of s_e at ψ values of –1 bar and –15 bars for each of the curves shown in Figure 24. The K(1) values for curves 6 through 8 are taken from Rawls et al. (1982), while the K(1) value for curve 5 is that computed for the sandiest soil in the model. Although Van Genuchten and Nielsen (1985) state that the Brooks and Corey (1964) model produces acceptable results for coarse textured soils at low moisture contents, Figure 24 appears to contradict that. In general, we have found that the values of s_e computed for sandy soils using the Brooks and Corey (1964) model are much too low. We chose to use the relationships developed by Rawls et al. (1982) because they appear to produce results that lie within the appropriate range of values, and are also relatively easy to compute.

7.5 Vegetation Characteristics

The final component of the relationship between physiological activities in the plant and soil moisture content is the response of the plant to low soil moisture potential (ψ). This varies considerably between species and vegetation types and is related to a number of plant characteristics. We are interested here in two critical points; those being the value of ψ at which stomatal closure begins and the value of ψ at which stomatal closure is complete. Since the stomata control the processes of transpiration and photosynthesis, closure will have a direct impact on the productivity of the plant.

Table 14 summarizes critical leaf and/or xylem ψ values for pines and deciduous trees as reported in the literature. Although specific studies have indicated differences (cf. Kozlowski, 1949; Croker, 1969), there is no clear indication from this summary that there is any significant difference between the vegetation types with respect to these critical values, so overall averages of both tree types were computed, resulting in an average value of –10.4 bars for the onset of stomatal closure and a value of –20.1 bars for complete stomatal closure.

These values are the values of ψ at the leaf when closure occurs, whereas we are concerned with the value of ψ at the root at the time closure occurs. Fitter and Hay (1987) state that gradients of approximately 0.2 bars per meter of height will occur in trees due both to resistances to flow and to gravitational effects. If we use an average

Table 14

Summary of Critical ψ Values

	Leaf or Xylem ψ (bars) at		
Species	Onset of Closure	Completion of Closure	Source
Loblolly pine	–4.5		Brix, 1962
Ponderosa pine		–17.3	Lopushinsky, 1969
Ponderosa pine		–16.5	Lopushinsky, 1969
Lodgepole pine		–16.2	Lopushinsky, 1969
Lodgepole pine		–14.6	Lopushinsky, 1969
Eastern white pine	–15	–28	Bunce et al., 1977
Pitch pine	–10.5	–18	Bunce et al., 1977
Stone pine	–0.4	–16	Havranek & Benecke, 1978
Walnut	–10	–25	Larcher, 1983
White oak	–17	–29	Hinckley et al., 1975
Black oak		–21.5	Hinckley et al., 1978
White oak		–21.0	Hinckley et al., 1978
Northern red oak		–16.0	Hinckley et al., 1978
Sugar maple		–15.5	Hinckley et al., 1978
Alder	–11	–16.5	Bunce et al., 1977
Green ash	–9	–19.5	Bunce et al., 1977
Northern red oak	–16.5	–30.5	Bunce et al., 1977
Averages:	–10.4	–20.1	

tree height of 30 meters (see chapter 3), this results in a gradient of 6 bars from the roots to the leaves at the top of the tree, which results in critical ψ values at the roots of -4.4 and -14.1 bars at the onset and completion of stomatal closure, respectively. There are additional gradients existing from the root into the soil around the roots, however these gradients are difficult to quantify without a complex soil moisture movement model, so we will neglect them here.

7.6 Application of Soil Moisture Constraints

We can look at the effects of soil moisture deficits on the trees in this region by translating these critical ψ values for the vegetation to s_e values based on soil type, and comparing them to the previously determined values of s_0. To do this, we first used equation (41) to compute K(1) as a function of latitude. We then used the Rawls et al. (1982) relationships described by curves 5 through 8 in Figure 24 to determine values of s_c versus latitude for the critical ψ values of -4.4 bars and -14.1 bars. These are plotted in Figure 25 along with the values of s_0 previously shown in Figure 21.

From Figure 25, we can see that the value of s_0 for the deciduous trees lies below the -4.4 bar ψ_c line at all points in this latitude range, and below the -14.1 bar ψ_c line at latitude less than 26° N, indicating that water stress is probably a factor throughout this region for the deciduous trees. In comparison, the s_0 line for the pine trees lies above the -4.4 bar ψ_c line at all points, indicating that water stress is probably not a problem for the pines in this region. However, it is not apparent from this figure why the pines do not dominate throughout the region if moisture stress is the operative limiting factor.

To gauge the effect of this soil moisture deficit on productivity, we made use of the soil moisture parameter W, which was discussed briefly in chapter 4. The effect of

ψ on W is characterized as follows:

$$\begin{aligned} &W = 1 && \text{for } \psi \geq -4.4 \text{ bars} \\ &W = 1.454 - 0.103\,\psi && \text{for } -4.4 \text{ bars} \leq \psi \leq -14.4 \text{ bars} \\ &W = 0 && \text{for } \psi \leq -14.1 \text{ bars} \end{aligned} \tag{59}$$

This relationship is shown graphically in Figure 26. A linear relationship between ψ and W was chosen due to the lack of more specific information.

To incorporate the information about interception, soil characteristics and vegetation response to moisture deficits into the productivity model, we developed a simple daily water balance submodel. We start at the beginning of the growing season with the previously computed value of s_0 (see Figure 21) and determine a value of ψ which corresponds to it using the relationship described by equation (57). We then determine W using equation (58), P_e using equation (30) and E_T using equation (3).

The effective water content of the active part of the soil column under a unit area of surface at time t can be expressed as

$$H_t = z_r\, n_e\, s_t \tag{60}$$

where

H_t = water content at time t (cm^3 H_2O cm^{-2} surface area)

z_r = soil depth (cm)

n_e = effective porosity (dimensionless)

s_t = soil moisture content at time t (dimensionless)

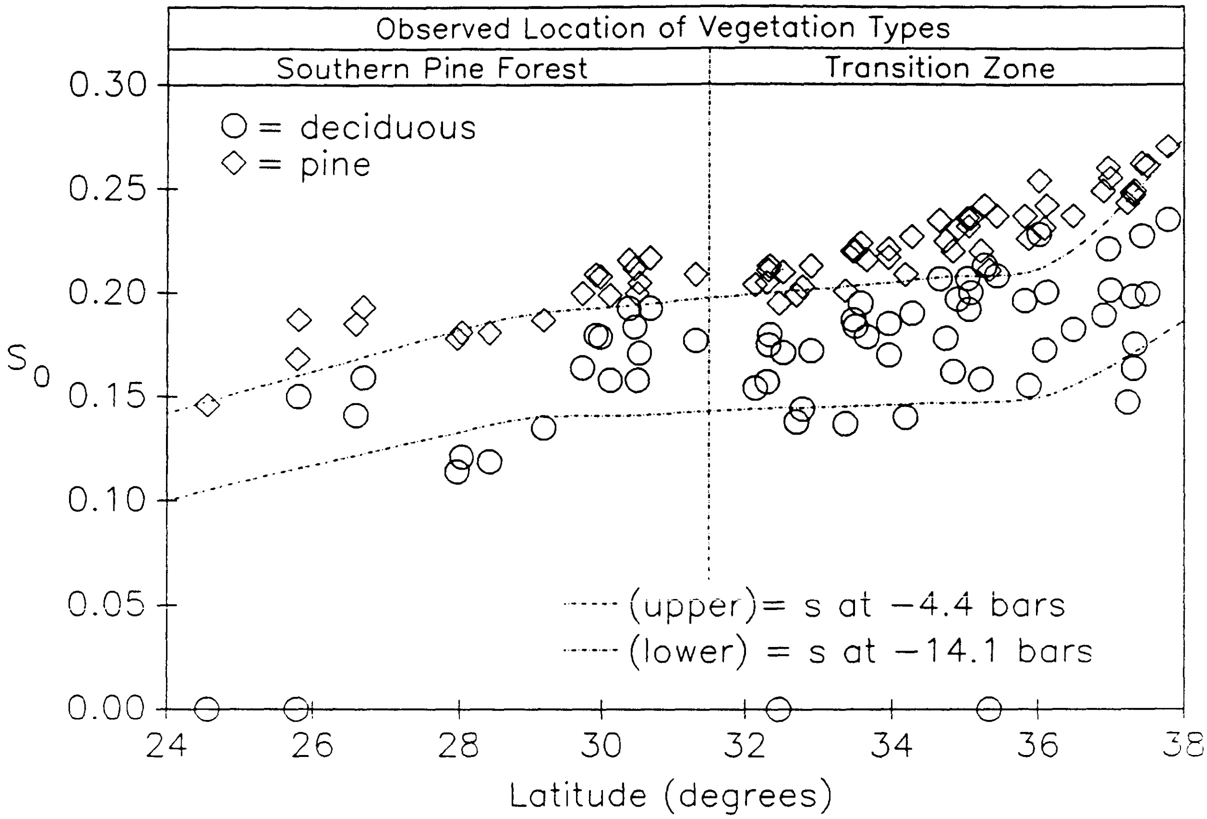

Figure 25: Comparison of critical soil moisture values with long term average soil moisture values in the southeast.

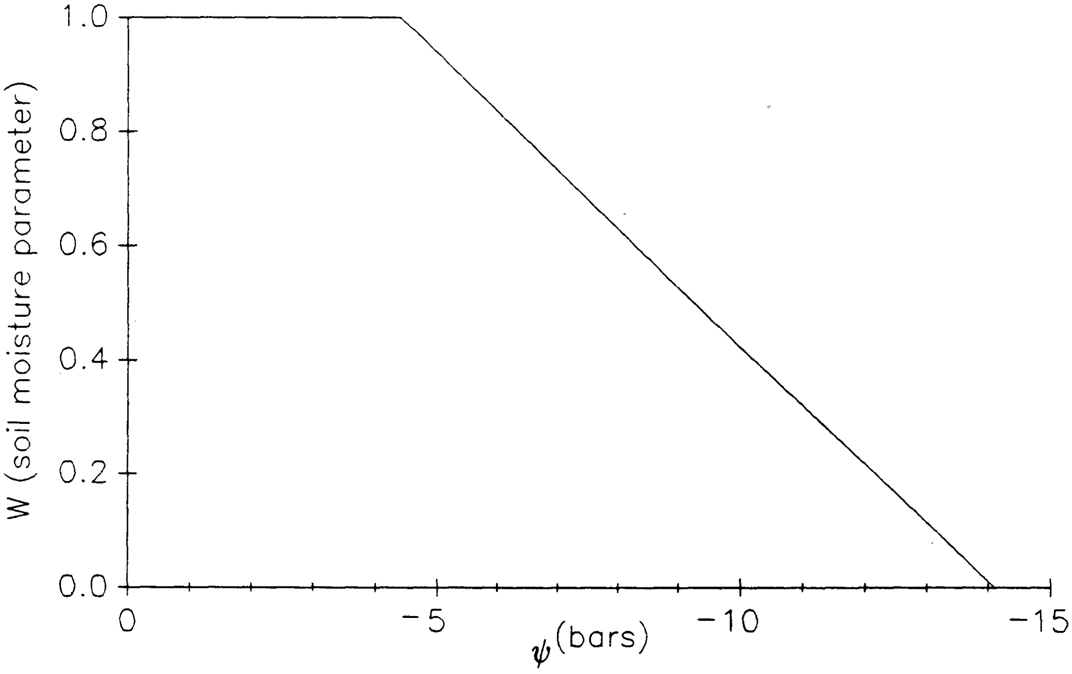

Figure 26: Relationship of ψ and W in the productivity model.

Soil depth was one of the pieces of information collected from the soil surveys discussed earlier. A plot of z_r against latitude is shown in Figure 27, with the following result:

$$z_r = 438 - 8.54\phi, \qquad R^2 = 0.48 \tag{61}$$

where ϕ is latitude.

The change in water content on a daily basis can be represented as

$$H_{t+1} = H_t + P_e - E_T - K(1)\left[\frac{s_t + s_{t+1}}{2}\right]^c \tag{62}$$

where P_e, E_T and $K(1)$ are in units of cm day^{-1}. Combining (60) and (62) and solving for s_{t+1}, we have

$$s_{t+1} = s_t + \frac{P_e}{z_r n_e} - \frac{E_T}{z_r n_e} - \frac{K(1)}{z_r n_e}\left[\frac{s_t + s_{t+1}}{2}\right]^c \tag{63}$$

This is solved iteratively until the difference between successive values of s_{t+1} is less than 0.001. A new value of ψ is then computed and the process as described above is then repeated each day for the entire growing season for both deciduous and pine vegetation types. Finally, NPP is determined from total E_T using equation (10). Figure 28 shows the results of these computations.

7.7 Discussion of Results

If Figure 28 is compared to Figure 15, it is clear that productivity in the

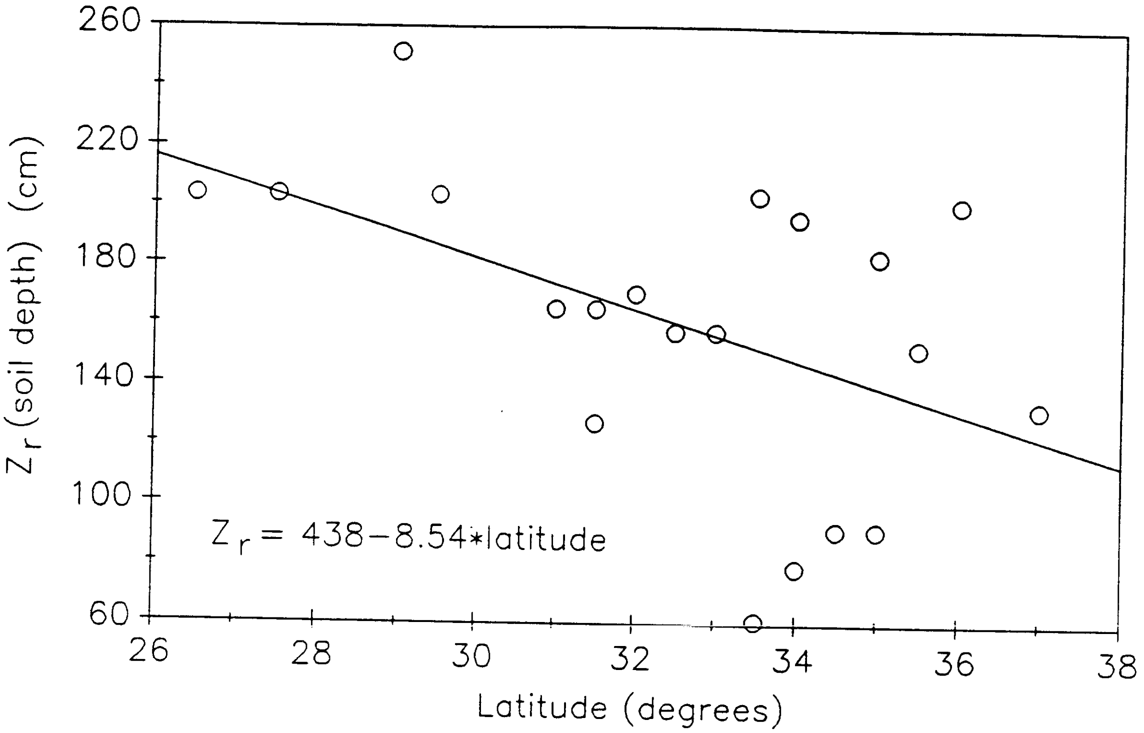

Figure 27: Soil depth versus latitude from soil survey data.

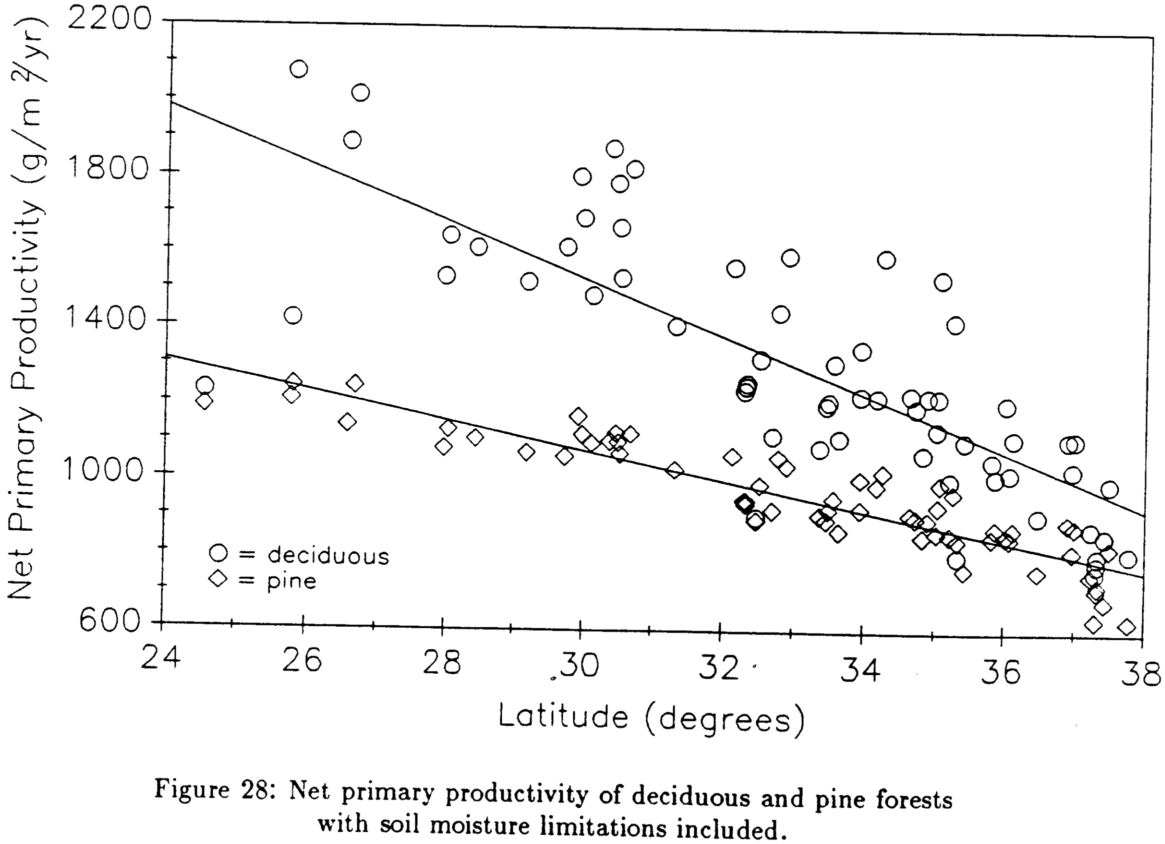

Figure 28: Net primary productivity of deciduous and pine forests with soil moisture limitations included.

deciduous trees has been substantially reduced by soil moisture limitations, although not enough to clearly demonstrate a competitive advantage for the pines. Several factors may be responsible for this.

First, this analysis relies heavily on the relationship of K(1) to latitude that we have postulated. The soils of this region are extremely variable, and while they apparently do get sandier on the average in the south, it should be remembered that this is only an average. The sparsity of "samples" which we used may lead to considerable inaccuracy in characterizing the change in soil texture in the southeast.

The analysis also relies on the assumed relationship of other soil properties (m, $\psi(1)$, z_r) to K(1). This is not strictly accurate, since K(1) as well as the other soil properties are all largely related to soil texture. We are using K(1) here as a convenient quantitative representation of the change in soil properties from north to south. This is not nearly as accurate as a direct representation of the change in each separate soil property with latitude would be. Unfortunately, there are practically no data available to perform such an analysis.

As can be seen from Figure 24, there is a great deal of variability in the relationship of soil characteristics to each other and many discrepancies in how these are characterized. Unfortunately, most experimental data that are available do not measure all of the parameters that are important in quantifying these interrelationships. Often an investigator must derive or assume values of parameters that were not measured, and that has occured in some of the data we have used here. The relationship of ψ and s_e is one of the most critical in assessing the impacts of moisture deficits on vegetation and our choice of models is somewhat arbitrary. A change in this relationship could have a dramatic effect on the results shown in Figures 26 and 28. The definition of threshhold values of ψ for stomatal closure is also based on a very small data set, and the linear relationship between ψ and W defined in equation (59) is purely hypothetical.

Our analysis of the long term average soil moisture and our simple daily water balance may not be detailed enough to accurately predict the occurrence of low soil moisture concentrations which adversely affect productivity. Physically–based models of soil moisture movement might provide a more accurate representation of daily changes in soil moisture, however they also require more information about soil and precipitation characteristics than are currently incorporated in this model.

Evaporation from the soil during the growing season has not been included based on the assumption that it will be negligible due to a heavy canopy cover. However, in pine forests the underbrush is often sparse and the canopy quite open, which may result in significant evaporation from the soil. Indeed, Denmead (1984) reports soil evaporation amounting to between 10 and 27 percent of total evaporation from a pine forest in Europe. Evaporation amounts of this magnitude could significantly affect soil moisture levels, however, further studies are needed to determine the relative importance of this component.

Although our model results indicate that the pine forest type would deplete soil moisture more slowly than the deciduous forest type, Zahner (1955) found no difference in rates of soil moisture depletion between stands of pine and deciduous trees in the same location. More studies similar to his should be carried out to assess the relative transpiration and soil moisture depletion rates of these vegetation types.

If we assume for a moment that the analysis of moisture limitations and their impact on productivity is reasonably accurate, we are left with the conclusion that yet another limiting factor is operating at this ecotone. As discussed earlier, we feel that the observed relationship between pine vegetation types and sandy soils is a clear indication that the limiting factor is in some way connected to soil properties.

A characteristic of sandy soils that we have not reviewed in detail is a tendency for them to be low in available nutrients. There are several reasons for this. The coarse texture of the sandy soil leads to more rapid percolation of water (see previous discussion of K(1)) which leads to more rapid leaching of nutrients from the root zone. These coarse textured soils are also better aerated, which encourages the rapid decomposition of organic matter. The resulting lower quantities of organic matter coupled with a smaller fraction of clay–sized particles dramatically reduces the available surface area and thus the nutrient holding capacity of the soil (Brady, 1974; Spurr and Barnes, 1980).

It has been suggested that evergreen species may dominate in areas of low nutrient availability (cf. Monk, 1966; Chabot and Hicks, 1982). There are a number of reasons for this hypothesis. Evergreen leaves tend to contain smaller quantities of several key nutrients. This reduces their uptake rates of these nutrients, which reduces their overall nutrient requirements that must be supplied by the soil. Evergreens also have more efficient internal nutrient cycling, which results in a higher carbon gain per unit of nutrient turned over. One study cited by Chabot and Hicks (1982) shows that evergreens have twice the carbon gain per unit of nitrogen turned over, which could result in a significant advantage in nutrient limited situations.

Although total quantities of litterfall are similar in deciduous and evergreen stands, the timing of litter fall is very different. Litter fall occurs year–round in evergreen stands, which ensures a constant, gradual release of nutrients to the soil through the decay process. In contrast, the bulk of deciduous leaves fall in the autumn, which leads to a large release of nutrients at a single time, usually in the spring when decomposition occurs. In areas with moderate amounts of precipitation and sandy soils that have low surface areas for nutrient adsorption, this large release of nutrients at a single time will result in a greater loss of these nutrients to leaching. Finally, evergreen leaves tend to decompose more slowly than deciduous leaves due to chemical and structural differences, again ensuring a gradual return of nutrients to the soil with less likelihood of loss through leaching from the root zone (Monk, 1966; Spurr and Barnes, 1980; Chabot and Hicks, 1982).

To determine the net effect of sandy soils on nutrient availability and productivity is beyond the scope of this model as it stands now, however we hope it will be incorporated in the future. Pastor and Post (1986) have used a more complex model to show that a combination of moisture and nutrient limitations might lead to conifer dominance on sandy soils in Minnesota under a warmer, drier climate. Information about nutrient uptake rates, foliar nutrient content, decay rates and removal by percolation must be combined somehow with information about the effects of nutrient limitations on productivity. We feel that including this information along with the relationships already developed in the model will be sufficient to predict the distribution of pine and deciduous vegetation types in the southeastern United States.

Chapter 8

Summary and Conclusions

Our goal in this study has been to formulate a simple, physically–based model which will enable us to predict the location of the two major vegetation ecotones in eastern North America. These ecotones are the deciduous forest/boreal forest ecotone in the north and the southern pine/deciduous forest ecotone in the south. Our hypothesis is that these boundaries are determined by the climatically–influenced relative competitive ability of each vegetation type at each location of interest. We further suggest that this competitive ability can be represented by biomass production, which can be computed for a given species j at any given location by

$$\mathrm{NPP_j}(\phi) = \alpha_j k_j \sum_{i=1}^{365} C_{j_i}\, W_{j_i}\, L_{j_i}\, E_{p_i}(\phi) \tag{10}$$

We reason that the species with the highest NPP in any given location will dominate at that location, and that ecotones will occur where a reversal in competitive abilities occurs due to the changing physical environment of the plant.

We tested this hypothesis in the absence of water limitations for the deciduous forest/boreal forest ecotone and found that the deciduous forests have a higher productivity and should thus be more competitive to a location slightly north of the observed ecotone. We suggest that freezing resistance may be the limiting factor for the deciduous forests in the north, whereas competitive ability is limiting the southward spread of the boreal forest. The transition zone between the two is probably due to differences in microclimate favoring one vegetation type over another.

We also tested this hypothesis with unlimited moisture for the southern pine/deciduous forest ecotone, with no success. We then looked at soil moisture limitations by determining the long term average soil moisture concentration for each vegetation type and comparing it to critical values at which photosynthesis and transpiration are affected. From this analysis, it appears that the deciduous trees are subject to some degree of moisture stress throughout the southeast, however there is no clear shift in behaviour that indicates a reason for the observed ecotone. We hypothesize that nutrient limitations may be the final limiting factor which must be considered, although we do not quantify it here.

The model has a number of weak spots, especially where data for estimating parameters are limited. Of special concern are the values of water use efficiency (α) and the crop coefficient (k). Very few direct measurements of these parameters are available for forest trees, and a change in either value could have a significant effect on model results. The characterization of photosynthetic response to temperature in conifers, and the effects of water limitations in both deciduous trees and conifers are also very rough and based on limited data.

As reviewed in Chapter 7, the characterization of soil properties is in need of a great deal of refinement. Additional information about the change in soil properties in the south would also be useful. All of these limitations are primarily due to a scarcity of field data. Studies need to be done with these specific data requirements in mind in order to more adequately represent some of these properties.

Biologists might argue that the model violates biological principles in at least two ways. First, it describes many individuals as one lumped, "average" individual; in essence assuming that all individuals are behaving identically. Second, the assumption is made that relative location is not important, that is, all individuals affect one another equally (Huston et al., 1988). Both of these arguments have merit, however, because of the temporal and spatial scales that we are concerned with we feel that this "averaging" of indivdual behaviour is both appropriate and necessary.

We feel that the results indicate that, with some refinement and the possible incorporation of other limiting factors, the productivity approach to ecotone prediction may be a useful addition to general circulation models. It should be possible to keep it relatively simple and still generate results which are accurate at the grid size of existing general circulation models. The model is, however, an equilibrium model and would require modification for the simulation of transient conditions. It is also evident from this study that any model which attempts to predict the location of major vegetation types should incorporate not only climatic factors but also soil characteristics, especially in regions where moisture or nutrients are likely to be limiting.

Chapter 9

Areas for Future Research

As mentioned previously, many of the parameters used in this model are based on very limited data. Field work to collect more data about both plant physiological processes and soil characteristics is sorely needed. This applies not only to the vegetation types considered in this study, but other vegetation types as well. Studies that are designed with specific data needs in mind will produce much more useful data than that which can be obtained from studies that were done for other reasons.

As this is essentially an equilibrium model, it does not attempt to account for generational time lags and migration effects. These transitional effects may actually prove to be quite significant given currently projected rates of climate change over the next century or two (Solomon and West, 1985). Several issues must be considered in this context.

First, the life span of a single tree may be several hundred years (see chapter 3). Once established, trees can endure long periods of relatively unfavorable conditions although this will probably restrict their reproduction (Brubaker, 1986). Although their natural life span may be shortened due to these adverse conditions, time lags of 100 years or more may occur before a new vegetation type can attain dominance in an area where conditions have changed.

This will aggravate the effects of the second area of concern, which is that of migration rates. If climate is changing rapidly, migration rates will be primarily a function of the distance which a given seed crop can travel from the parent tree and how long it takes each crop of seedlings to reach reproductive maturity and continue the process (Sauer, 1988). This could be especially critical if changes are occuring so fast that an unfavorable zone creates a barrier separating the migrating "front" from the region in which it can survive. Migration rates of temperate forest species after the last glaciation, as derived from fossil pollen analysis, ranged from 10 to 200 km per century (Huntley and Birks, 1983; Davis, 1987; Roberts, 1989). According to most projections of climate change over the next century, favorable conditions for each vegetation type could shift several hundred kilometers in the same amount of time. It may become necessary for humans to facilitate the migration process in order to avoid the potential loss of forests in some areas during this time.

It would be a useful exercise to include information about longevity and migration rates in the productivity model as it is currently formulated. This would enable testing to determine if predictions of the demise of certain forests in North America are warranted (Cohn, 1989; Roberts, 1989). Since many of the previous projections of this type have been based on empirical determinations for species range limits, this may provide new insights into this problem.

Finally, there is the question of the applicability of this model to other vegetation types and ecotones. We feel that the general method has a great deal of potential. It should be a relatively easy task to incorporate information on temperature and moisture limitations (assuming that the data are available) for tropical forest species into the model as it stands now. This would allow prediction of the boundaries between temperate and tropical forests. Similar information could be gathered for the deciduous conifers (larches) of northern Europe and Asia. This would allow the prediction of vegetation types throughout those continents if climate data are available. This work could also be done with the forests of Australia and possibly with savannah vegetation as well.

Predicting changes between major plant life forms (i.e., grass to forest, etc.) may be more difficult. It will most likely involve some determination of the levels of production below which a given life form cannot survive, and using this in conjunction with the existing model for determining production levels. In general, forests have the highest net productivities of any terrestrial vegetation type, followed by savannah, grasslands, and finally tundra and desert communities (Whittaker, 1975). It should be feasible to combine the basic competitive hypothesis of this model with information on how life form may affect that competitive ability.

The most difficult areas to predict vegetation types for will be those areas that have suffered anthropogenic influences such as deforestation or agriculture. As the population of the earth increases, these areas will encompass more and more of the planet. As human pressures on ecosystems increase, models such as the one described here may be used more for indicating potential vegetation types than for predicting what may actually exist at a given site. Of course, humans can also have a beneficial impact through such activites as reforestation. In this case, the model could serve as an aid in determining the type of vegetation that would have the greatest chances for success in such a revegetation program.

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Appendix A: Table 1

Climatic Data: Station Information

Station Number	City	State	Latitude	Longitude	Elev. (ft.)
010829	Birmingham City	Alabama	33.47	86.83	744
010831	Birmingham	Alabama	33.57	86.75	620
014064	Huntsville	Alabama	34.65	86.77	600
015478	Mobile	Alabama	30.68	88.25	211
015550	Montgomery	Alabama	32.30	86.40	183
032574	Fort Smith	Arkansas	35.33	94.37	447
034248	Little Rock	Arkansas	34.73	92.23	257
035320	North Little Rock	Arkansas	34.83	92.27	563
060806	Bridgeport	Connecticut	41.17	73.13	7
063456	Hartford	Connecticut	41.93	72.68	169
079595	Wilmington-Newcastle	Delaware	39.67	75.60	74
080211	Apalachicola	Florida	29.73	85.03	13
082158	Daytona Beach	Florida	29.18	81.07	30
083186	Fort Myers	Florida	26.58	81.87	15
084358	Jacksonville	Florida	30.50	81.82	24
084570	Key West	Florida	24.55	81.75	4
084797	Lakeland	Florida	28.03	81.95	214
085658	Miami Beach	Florida	25.78	80.13	5
085663	Miami	Florida	25.80	80.27	7
086628	Orlando – McCoy AFB	Florida	28.43	81.33	9
086997	Pensacola	Florida	30.47	87.20	112
088758	Tallahassee	Florida	30.38	84.37	55
088788	Tampa	Florida	27.97	82.53	19
089525	West Palm Beach	Florida	26.68	80.10	15
090435	Athens	Georgia	33.95	83.32	802
090451	Atlanta	Georgia	33.65	84.43	1010
090495	Augusta	Georgia	33.37	81.97	145
092166	Columbus	Georgia	32.52	84.95	385
095443	Macon	Georgia	32.70	83.65	354
097847	Savannah	Georgia	32.13	81.20	46
111166	Cairo	Illinois	37.00	89.17	314
111549	Chicago – OHare	Illinois	41.98	87.90	658
115751	Moline	Illinois	41.45	90.50	582
116711	Peoria	Illinois	40.67	89.68	652
117072	Quincy Airport	Illinois	39.93	91.20	763
117382	Rockford	Illinois	42.20	89.10	724
118179	Springfield	Illinois	39.83	89.68	588
122738	Evansville	Indiana	38.05	87.53	381
123037	Fort Wayne	Indiana	41.00	85.20	791
124259	Indianapolis	Indiana	39.73	86.27	792
128187	South Bend	Indiana	41.70	86.32	773
132203	Des Moines	Iowa	41.53	93.65	938
132367	Dubuque	Iowa	42.40	90.70	1056
135235	Mason City Airport	Iowa	43.17	93.33	1194
137708	Sioux City	Iowa	42.40	96.38	1103
138706	Waterloo	Iowa	42.55	92.40	868
150909	Bowling Green Airport	Kentucky	36.97	86.43	535

Appendix A: Table 1
(continued)

Station Number	City	State	Latitude	Longitude	Elev. (ft.)
151855	Covington	Kentucky	39.07	84.67	869
154202	Jackson Airport	Kentucky	37.43	83.32	1365
154746	Lexington	Kentucky	38.03	84.60	966
154954	Louisville	Kentucky	38.18	85.73	477
160098	Alexandria	Lousiana	31.32	92.47	87
160549	Baton Rouge	Lousiana	30.53	91.13	64
165078	Lake Charles	Lousiana	30.12	93.22	9
166660	New Orleans Moisant	Lousiana	29.98	90.25	4
166664	New Orleans Audubon	Lousiana	29.92	90.13	6
168440	Shreveport	Lousiana	32.47	93.82	254
170355	Bangor Airport	Maine	44.80	68.82	160
171175	Caribou	Maine	46.87	68.02	624
176905	Portland	Maine	43.65	70.32	43
180465	Baltimore	Maryland	39.18	76.67	148
180470	Baltimore City	Maryland	39.28	76.62	14
188005	Salisbury Airport	Maryland	38.33	75.50	48
190736	Blue Hill	Massachusetts	42.22	71.12	629
190770	Boston	Massachusetts	42.37	71.03	15
191386	Chatham	Massachusetts	41.67	69.97	50
195159	Nantucket Airport	Massachusetts	41.25	70.07	40
199923	Worcester	Massachusetts	42.27	71.87	986
200164	Alpena	Michigan	45.07	83.57	689
202103	Detroit Metro. Airport	Michigan	42.23	83.33	633
202846	Flint	Michigan	42.97	83.75	770
203333	Grand Rapids/Kent	Michigan	42.88	85.52	784
203908	Houghton Airport	Michigan	47.17	88.50	1081
203936	Houghton Lake	Michigan	44.37	84.68	1149
204641	Lansing	Michigan	42.77	84.60	841
205178	Marquette	Michigan	46.55	87.38	665
205184	Marquette Airport	Michigan	46.53	87.55	1415
205712	Muskegon	Michigan	43.17	86.23	627
207227	Saginaw Airport	Michigan	43.53	84.08	660
207366	Sault Ste Marie	Michigan	46.47	84.37	721
208251	Traverse City Airport	Michigan	44.73	85.58	618
210112	Alexandria Airport	Minnesota	45.87	95.38	1421
212248	Duluth	Minnesota	46.83	92.18	1428
214026	International Falls	Minnesota	48.57	93.38	1179
215435	Minneapolis/St. Paul	Minnesota	44.88	93.22	834
217004	Rochester	Minnesota	43.92	92.50	1297
217294	St. Cloud	Minnesota	45.55	94.07	1034
223627	Greenwood Airport	Mississippi	33.50	90.20	128
224472	Jackson	Mississippi	32.32	90.08	31
225776	Meridian	Mississippi	32.33	88.75	290
231791	Columbia Region	Missouri	38.82	92.22	887
234358	Kansas City	Missouri	39.32	94.72	1014
234359	Kansas City Airport	Missouri	39.12	94.60	742
237435	St. Joseph	Missouri	39.77	94.92	811
237455	Saint Louis	Missouri	38.75	90.38	535
237976	Springfield	Missouri	37.23	93.38	1268

Appendix A: Table 1
(continued)

Station Number	City	State	Latitude	Longitude	Elev. (ft.)
271683	Concord	New Hampshire	43.20	71.50	346
275639	Mt. Washington	New Hampshire	44.27	71.30	6262
280311	Atlantic City	New Jersey	39.45	74.57	64
280325	Atlantic City Marina	New Jersey	39.38	74.43	11
286026	Newark	New Jersey	40.70	74.17	11
288883	Trenton	New Jersey	40.22	74.77	56
300042	Albany	New York	42.75	73.80	275
300687	Binghamton	New York	42.22	75.98	1590
301012	Buffalo	New York	42.93	78.73	705
305134	Massena Airport	New York	44.93	74.85	214
305801	New York Central Park	New York	40.78	73.97	132
305803	New York JFK Airport	New York	40.65	73.78	13
305811	New York LaGuardia	New York	40.77	73.90	11
307167	Rochester	New York	43.12	77.67	547
308383	Syracuse	New York	43.12	76.12	410
310300	Asheville	North Carolina	35.43	82.55	2140
311458	Cape Hatteras	North Carolina	35.27	75.55	7
311690	Charlotte	North Carolina	35.22	80.93	735
313630	Greensboro	North Carolina	36.08	79.95	897
316108	New Bern Airport	North Carolina	35.08	77.03	18
317069	Raleigh/Durham	North Carolina	35.87	78.78	434
319457	Wilmington	North Carolina	34.27	77.90	28
330058	Akron/Canton	Ohio	40.92	81.43	1208
331561	Cincinnati Abbe	Ohio	39.15	84.52	760
331657	Cleveland	Ohio	41.42	81.87	777
331786	Columbus	Ohio	40.00	82.88	812
332075	Dayton	Ohio	39.90	84.20	1002
334865	Mansfield	Ohio	40.82	82.52	1295
338357	Toledo Express	Ohio	41.58	83.80	669
339406	Youngstown	Ohio	41.27	80.67	1178
360106	Allentown	Pennsylvania	40.65	75.43	387
360865	Bradford Airport	Pennsylvania	41.80	78.63	2142
362682	Erie	Pennsylvania	42.08	80.18	732
363699	Harrisburg	Pennsylvania	40.22	76.85	338
366889	Philadelphia	Pennsylvania	39.88	75.23	5
366993	Pittsburgh Airport	Pennsylvania	40.50	80.22	1137
369705	Wilkes–Barre/Scranton	Pennsylvania	41.33	75.73	930
369728	Williamsport	Pennsylvania	41.25	76.92	524
370896	Block Island	Rhode Island	41.17	71.58	110
376698	Providence	Rhode Island	41.73	71.43	51
381544	Charleston Airport	South Carolina	32.90	80.03	41
381549	Charleston City	South Carolina	32.78	79.93	9
381939	Columbia	South Carolina	33.95	81.12	213
383106	Florence Airport	South Carolina	34.18	79.72	146
383747	Greenville/Spartanburg	South Carolina	34.90	82.22	957
401094	Bristol	Tennessee	36.48	82.40	1525
401656	Chattanooga	Tennessee	35.03	85.20	665
404950	Knoxville	Tennessee	35.82	83.98	980
405954	Memphis	Tennessee	35.05	90.00	263

Appendix A: Table 1
(continued)

Station Number	City	State	Latitude	Longitude	Elev. (ft.)
406402	Nashville	Tennessee	36.12	86.68	590
406750	Oak Ridge	Tennessee	36.02	84.23	905
431081	Burlington	Vermont	44.47	73.15	332
445120	Lynchburg	Virginia	37.33	79.20	916
446139	Norfolk	Virginia	36.90	76.20	22
447201	Richmond	Virginia	37.50	77.33	164
447285	Roanoke	Virginia	37.32	79.97	1149
448903	Washington Dulles	DC	38.95	77.45	291
448906	Washington National	DC	38.85	77.03	10
460582	Beckley	West Virginia	37.78	81.12	2504
460921	Bluefield Airport	West Virginia	37.30	81.22	2870
461570	Charleston	West Virginia	38.37	81.60	939
462718	Elkins	West Virginia	38.88	79.85	1992
464393	Huntington	West Virginia	38.37	82.55	827
464763	Kearneysville	West Virginia	39.38	77.88	550
466859	Parkersburg	West Virginia	39.27	81.57	615
472428	Eau Claire Airport	Wisconsin	44.87	91.48	888
473269	Green Bay Airport	Wisconsin	44.48	88.13	682
474370	La Crosse Airport	Wisconsin	43.87	91.15	651
474961	Madison	Wisconsin	43.13	89.33	858
475479	Milwaukee	Wisconsin	42.95	87.90	672
478968	Wausau Airport	Wisconsin	44.92	89.62	1196
Canadian Stations					
511582	Quebec Airport	Quebec	46.80	71.38	246
512582	Sept Iles Airport	Quebec	50.22	66.27	180
511882	Sherbrooke Airport	Quebec	45.43	71.68	791
512682	Sudbury Airport	Ontario	46.62	80.80	1139
512482	Thunder Bay Airport	Ontario	48.37	89.32	646
510182	Toronto	Ontario	43.67	79.40	364

Appendix A: Table 2

Evapotranspiration Values for Computing Hamon Correction Factor, F

Station number	Latitude	Pan Evaporation	Map Coefficient	Actual Evaporation	Calculated Evaporation	F
010831	33.57	56.18	0.76	42.70	35.26	1.21
015478	30.68	60.91	0.76	46.29	40.09	1.15
015550	32.30	58.70	0.76	44.61	37.85	1.18
032574	35.33	56.61	0.76	43.02	35.40	1.22
034248	34.73	58.42	0.76	44.40	36.11	1.23
060806	41.17	42.16	0.77	32.46	27.13	1.20
063456	41.93	42.53	0.76	32.32	26.29	1.23
079595	39.67	46.51	0.78	36.28	29.11	1.25
082158	29.18	66.07	0.76	50.21	41.73	1.20
084358	30.50	67.65	0.76	51.41	39.86	1.29
084570	24.55	87.00	0.74	64.38	50.35	1.28
085663	25.80	74.97	0.74	55.48	47.38	1.17
086628	28.43	72.39	0.75	54.29	44.34	1.22
088758	30.38	58.57	0.76	44.51	39.37	1.13
088788	27.97	72.60	0.74	53.72	43.81	1.23
089525	26.68	75.29	0.74	55.71	46.11	1.21
090435	33.95	55.01	0.74	40.71	34.29	1.19
090451	33.65	57.13	0.74	42.28	34.04	1.24
090495	33.37	55.09	0.74	40.77	36.07	1.13
092166	32.52	54.91	0.74	40.63	37.20	1.09
095443	32.70	62.16	0.74	46.00	37.69	1.22
097847	32.13	61.82	0.75	46.37	38.37	1.21
111549	41.98	52.02	0.76	39.54	26.30	1.50
115751	41.45	46.58	0.76	35.40	27.33	1.30
116711	40.67	48.06	0.73	35.08	27.61	1.27
117382	42.20	44.88	0.77	34.56	25.80	1.34
118179	39.83	52.70	0.72	37.94	29.18	1.30
122738	38.05	52.29	0.74	38.69	31.07	1.25
123037	41.00	46.39	0.73	33.86	26.42	1.28
124259	39.73	46.61	0.73	34.03	28.19	1.21
128187	41.70	42.56	0.76	32.35	26.02	1.24
132203	41.53	49.38	0.76	37.53	27.98	1.34
137708	42.40	46.03	0.74	34.06	27.39	1.24
138706	42.55	42.85	0.77	32.99	25.15	1.31
154746	38.03	48.57	0.75	36.43	29.67	1.23
154954	38.18	51.13	0.75	38.35	31.08	1.23
160098	31.32	52.00	0.74	38.48	39.33	0.98
160549	30.53	59.34	0.76	45.10	39.94	1.13
165078	30.12	60.13	0.74	44.50	40.32	1.10
166660	29.98	57.96	0.76	44.05	40.46	1.09
168440	32.47	64.55	0.74	47.77	38.77	1.23
176905	43.65	35.53	0.76	27.00	22.19	1.22
180465	39.18	52.07	0.78	40.61	30.03	1.35
190770	42.37	50.09	0.76	38.07	26.88	1.42
195159	41.25	37.21	0.78	29.02	23.40	1.24
199923	42.27	40.96	0.76	31.13	23.50	1.32

Appendix A: Table 2
(continued)

Station number	Latitude	Pan Evaporation	Map Coefficient	Actual Evaporation	Calculated Evaporation	F
200164	45.07	33.66	0.80	26.93	20.91	1.29
202103	42.23	42.50	0.74	31.45	25.41	1.24
202846	42.97	38.57	0.75	28.93	24.00	1.21
203333	42.88	42.29	0.77	32.56	24.80	1.31
204641	42.77	41.19	0.75	30.89	24.49	1.26
205712	43.17	42.80	0.78	33.38	24.07	1.39
207366	46.47	31.21	0.80	24.97	19.55	1.28
212248	46.83	35.22	0.80	28.18	19.79	1.42
214026	48.57	33.61	0.80	26.89	20.26	1.33
215435	44.88	44.15	0.80	35.32	25.20	1.40
217004	43.92	42.06	0.80	33.65	23.58	1.43
224472	32.32	55.70	0.76	42.33	37.73	1.12
225776	32.33	54.52	0.76	41.44	36.93	1.12
231791	38.82	54.89	0.74	40.62	30.06	1.35
234359	39.12	58.43	0.74	43.24	32.96	1.31
237455	38.75	54.18	0.73	39.55	31.40	1.26
237976	37.23	54.51	0.75	40.88	30.83	1.33
271683	43.20	34.44	0.76	26.17	23.03	1.14
280311	39.45	47.77	0.78	37.26	27.72	1.34
286026	40.70	49.69	0.78	38.76	29.68	1.31
300042	42.75	38.40	0.76	29.18	24.59	1.19
300687	42.22	36.20	0.76	27.51	22.83	1.21
301012	42.93	40.89	0.77	31.49	24.36	1.29
305811	40.77	54.55	0.78	42.55	29.48	1.44
307167	43.12	40.24	0.77	30.98	24.82	1.25
308383	43.12	38.97	0.76	29.62	24.64	1.20
311458	35.27	56.45	0.78	44.03	34.06	1.29
311690	35.22	58.08	0.75	43.56	33.25	1.31
313630	36.08	51.72	0.74	38.27	31.42	1.22
317069	35.87	54.29	0.72	39.09	32.33	1.21
319457	34.27	58.35	0.77	44.93	36.12	1.24
330058	40.92	40.94	0.76	31.11	25.53	1.22
331657	41.42	44.07	0.76	33.49	25.59	1.31
331786	40.00	43.69	0.76	33.20	27.38	1.21
332075	39.90	49.34	0.74	36.51	27.84	1.31
338357	41.58	42.23	0.74	31.25	25.33	1.23
339406	41.27	39.04	0.77	30.06	24.41	1.23
360106	40.65	41.73	0.76	31.71	26.86	1.18
362682	42.08	42.82	0.77	32.97	23.60	1.40
363699	40.22	48.52	0.76	36.88	28.68	1.29
366889	39.88	49.60	0.78	38.69	29.53	1.31
366993	40.50	43.62	0.77	33.59	25.97	1.29
369728	41.25	37.53	0.76	28.52	26.14	1.09
376698	41.73	45.33	0.76	34.45	25.81	1.33
381544	32.90	59.94	0.75	44.95	37.18	1.21
381939	33.95	59.37	0.73	43.34	36.45	1.19
383747	34.90	56.63	0.76	43.04	33.14	1.30
401094	36.48	44.70	0.78	34.87	29.50	1.18

Appendix A: Table 2
(continued)

Station number	Latitude	Pan Evaporation	Map Coefficient	Actual Evaporation	Calculated Evaporation	F
401656	35.03	49.94	0.78	38.95	33.02	1.18
404950	35.82	50.61	0.78	39.48	32.36	1.22
405954	35.05	61.37	0.76	46.64	36.17	1.29
406402	36.12	53.41	0.78	41.66	33.35	1.25
431081	44.47	35.02	0.78	27.32	22.95	1.19
445120	37.33	47.97	0.76	36.46	29.85	1.22
446139	36.90	56.25	0.76	42.75	32.90	1.30
447201	37.50	51.50	0.74	38.11	31.74	1.20
447285	37.32	52.89	0.78	41.25	29.86	1.38
461570	38.37	42.45	0.77	32.69	29.02	1.13
462718	38.88	32.00	0.78	24.96	24.05	1.04
473269	44.48	37.30	0.79	29.47	22.92	1.29
474370	43.87	43.36	0.80	34.69	25.54	1.36
474961	43.13	40.46	0.77	31.15	23.82	1.31
475479	42.95	42.62	0.77	32.82	23.77	1.38

Appendix A: Table 3

Climatic Data Used to Determine Elapsed Degree Days

Wauseon, Ohio
1883
data source: Smith, 1915

day of month	Daily Temperature Extremes (°F)									
	January		February		March		April		May	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	27	16	10	–4	60	32	35	24	67	40
2	28	2	17	5	51	30	42	18	73	34
3	28	8	34	13	33	16	48	22	83	45
4	18	6	33	12	31	14	58	34	72	44
5	23	14	16	2	30	7	56	44	56	44
6	28	17	17	–2	38	25	48	31	68	33
7	28	21	25	12	23	12	42	30	81	54
8	29	0	27	0	32	3	56	25	68	50
9	23	–16	29	7	49	19	70	39	77	46
10	17	–10	17	–12	39	23	70	39	73	50
11	23	–4	33	16	28	16	58	42	61	32
12	20	–6	38	0	39	19	56	42	63	36
13	36	13	43	4	51	27	56	39	58	27
14	14	–1	35	23	62	27	84	44	70	42
15	24	–8	42	34	50	22	74	48	64	42
16	32	9	60	37	33	13	60	41	67	38
17	36	22	37	16	52	27	70	37	68	35
18	32	15	26	12	69	14	76	45	72	52
19	35	22	32	20	21	7	65	42	82	62
20	34	20	42	24	29	–17	60	35	62	52
21	21	–10	32	19	34	–5	61	37	52	32
22	–2	–18	33	26	33	–8	47	36	40	33
23	2	–13	29	17	33	15	48	30	68	36
24	29	–7	40	19	42	–1	39	21	76	35
25	20	2	44	24	41	17	56	25	80	56
26	28	–2	25	14	44	28	67	34	69	49
27	40	27	31	10	40	26	69	36	67	38
28	32	21	44	23	34	26	52	34	65	48
29	38	18			41	26	55	20	71	47
30	43	31			42	28	62	25	65	46
31	19	8			39	22			63	46

Appendix A: Table 3
(continued)

Wauseon, Ohio
1884
data source: Smith, 1915

Daily Temperature Extremes (° F)

day of month	January		February		March		April		May	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	29	17	28	0	20	1	48	35	79	41
2	23	8	42	25	24	–4	36	31	64	41
3	10	3	30	21	23	6	51	26	68	32
4	0	–19	28	21	24	–8	61	29	64	48
5	2	–24	50	28	30	5	53	25	76	57
6	1	–25	32	31	38	5	54	22	67	54
7	15	–19	31	24	28	19	56	23	61	48
8	17	–5	35	23	25	15	44	28	62	51
9	22	7	34	25	29	18	44	30	69	45
10	34	2	28	21	33	–2	46	30	68	38
11	34	4	29	21	52	27	51	28	67	42
12	24	6	37	28	51	27	58	28	72	40
13	44	10	45	30	55	27	56	38	63	46
14	37	18	31	0	38	24	71	40	66	37
15	22	4	26	6	41	18	60	47	72	49
16	21	2	43	13	46	18	48	34	63	32
17	34	12	40	30	53	40	50	31	74	35
18	34	20	45	33	41	30	55	26	78	48
19	30	6	58	32	39	32	58	40	68	51
20	16	–13	34	14	39	31	53	35	75	46
21	14	–11	36	17	48	32	48	31	82	46
22	35	7	39	13	57	29	46	33	80	56
23	31	6	28	12	63	42	56	35	82	63
24	12	–20	28	13	59	34	67	40	72	57
25	12	–32	34	24	53	42	70	34	74	47
26	34	–8	35	24	50	38	73	33	64	56
27	25	7	36	18	65	30	76	43	69	46
28	38	20	19	–8	54	40	72	42	58	37
29	36	32	13	–7	53	32	61	32	65	29
30	50	32			48	20	79	43	74	38
31	33	19			45	27			75	44

Appendix A: Table 3
(continued)

Wauseon, Ohio
1885
data source: Smith, 1915

Daily Temperature Extremes (°F)

day of month	January		February		March		April		May	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	21	5	31	5	41	27	59	29	57	39
2	16	2	21	–6	36	20	62	31	58	39
3	25	4	44	21	43	26	39	25	54	21
4	35	12	39	28	36	31	44	12	62	34
5	41	22	28	–3	38	20	63	34	67	45
6	47	30	13	–14	38	16	60	27	59	52
7	39	27	28	9	32	22	61	38	52	40
8	48	25	34	14	31	0	57	27	51	34
9	43	24	20	10	39	6	34	21	47	35
10	34	15	10	–19	37	16	47	18	45	32
11	44	24	2	–24	32	7	42	33	65	27
12	45	13	18	–6	30	18	47	30	61	41
13	20	6	16	–24	30	9	35	25	72	36
14	27	2	31	–17	44	17	40	18	76	39
15	29	19	40	5	39	17	45	32	78	41
16	24	14	33	–11	18	4	47	35	81	47
17	17	–10	11	–15	18	–2	40	34	83	49
18	2	–18	17	–9	28	6	43	37	81	52
19	0	–25	8	–7	19	0	65	41	68	42
20	9	–23	10	–13	12	–7	75	45	77	43
21	9	–13	14	–14	21	–6	78	54	80	52
22	8	–29	23	–17	23	–2	79	54	67	61
23	22	–14	31	0	28	2	82	55	74	60
24	33	16	31	4	35	20	68	47	82	56
25	28	10	34	16	35	13	52	37	77	57
26	15	–11	38	23	52	28	63	40	80	49
27	3	–13	44	26	47	32	68	38	73	52
28	6	–27	51	24	45	25	62	38	70	48
29	16	–26			41	24	64	27	77	56
30	36	8			46	27	58	43	72	58
31	32	–2			56	31			77	59

Appendix A: Table 3
(continued)

Wauseon, Ohio
1886
data source: Smith, 1915

Daily Temperature Extremes (° F)

day of	January		February		March		April		May	
month	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	45	32	21	8	26	5	37	28	60	43
2	38	31	11	–4	29	6	39	23	73	38
3	52	37	12	–10	38	9	39	19	70	38
4	52	31	11	–12	42	17	40	24	73	56
5	32	17	13	–18	38	16	39	20	72	50
6	25	9	30	13	48	16	32	26	75	38
7	16	3	28	23	44	19	46	26	66	45
8	16	10	50	22	34	26	58	14	74	34
9	18	11	52	30	33	21	60	22	62	51
10	12	–8	52	36	39	24	60	36	70	52
11	5	–13	57	40	46	20	50	37	76	49
12	7	–4	51	36	40	33	65	38	82	52
13	20	2	42	33	39	27	69	40	79	52
14	32	4	38	31	37	24	81	44	80	61
15	31	13	31	20	64	27	78	47	65	44
16	37	22	21	8	43	26	81	47	59	37
17	22	9	40	6	47	24	79	50	67	32
18	27	14	48	28	64	30	78	48	74	38
19	32	6	40	16	75	34	78	45	79	43
20	30	7	26	9	68	51	75	47	81	47
21	34	17	35	18	55	32	79	43	83	40
22	27	–2	38	16	34	28	83	45	89	64
23	13	–14	38	24	42	21	84	50	86	60
24	24	–4	49	20	58	21	78	52	77	54
25	35	16	48	16	51	42	78	47	63	37
26	32	27	23	8	55	30	80	42	73	37
27	33	28	23	9	39	26	65	46	72	53
28	30	26	22	8	40	22	76	40	78	44
29	29	20			54	33	68	44	81	50
30	20	7			47	36	54	44	84	52
31	20	–1			46	34			81	47

Appendix A: Table 3
(continued)

Wauseon, Ohio
1887
data source: Smith, 1915

day	Daily Temperature Extremes (° F)									
of	January		February		March		April		May	
month	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	23	–1	15	0	51	26	52	24	73	50
2	13	–13	27	15	62	34	59	22	82	60
3	5	–8	31	18	35	24	76	37	72	54
4	19	–6	27	8	37	20	64	21	71	44
5	24	2	23	14	32	18	42	18	60	50
6	15	–6	38	23	54	32	46	19	74	44
7	18	–20	48	33	57	33	50	33	74	51
8	12	–8	56	34	56	26	69	27	78	54
9	18	9	42	24	58	28	80	32	77	51
10	11	–8	52	31	50	27	80	42	76	52
11	23	–15	51	19	42	23	84	54	80	55
12	28	19	20	12	52	30	84	33	80	51
13	31	16	28	6	50	18	68	37	85	45
14	35	25	37	18	31	17	78	34	72	46
15	27	20	41	34	36	18	74	45	84	40
16	32	17	39	29	41	19	49	35	83	48
17	36	1	37	24	36	19	43	28	63	54
18	10	–5	49	28	36	18	39	28	75	45
19	31	–4	32	23	49	25	56	17	84	40
20	46	30	29	23	52	20	61	32	89	49
21	36	14	32	22	42	32	66	38	92	58
22	57	33	41	21	34	21	60	47	89	56
23	59	35	34	25	42	14	61	36	87	58
24	38	28	34	18	55	30	52	30	79	57
25	46	32	32	14	44	23	53	34	68	50
26	32	–1	45	21	39	15	57	35	64	45
27	34	0	21	11	32	23	61	32	74	44
28	44	29	31	10	28	14	62	42	81	48
29	43	25			25	7	60	41	81	45
30	36	3			39	7	68	32	65	58
31	8	1			45	18			72	53

Appendix A: Table 3
(continued)

Wauseon, Ohio
1888
data source: Smith, 1915

day of month	Daily Temperature Extremes (°F) January		February		March		April		May	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	41	15	32	26	41	32	65	32	44	31
2	19	11	38	22	58	31	51	32	58	23
3	25	13	32	14	31	20	50	23	79	40
4	38	19	35	28	20	12	62	24	68	46
5	34	28	34	20	27	10	74	40	68	45
6	44	29	29	11	33	9	57	36	80	42
7	44	32	36	19	38	12	58	36	81	44
8	38	19	20	1	44	16	52	25	76	44
9	27	19	10	–8	45	22	61	30	73	55
10	21	8	20	–9	45	35	58	41	77	45
11	13	0	26	9	44	20	63	33	84	56
12	32	–7	37	4	26	12	49	31	66	40
13	39	5	46	20	27	8	55	26	48	33
14	32	–1	37	19	38	11	57	40	46	36
15	25	0	19	–4	50	19	46	34	58	33
16	15	–6	38	1	45	31	55	35	61	40
17	22	11	43	26	33	25	65	33	64	30
18	15	4	50	30	45	19	57	38	56	44
19	19	0	47	30	71	34	48	36	62	39
20	18	8	49	24	56	34	46	28	67	30
21	11	–7	39	23	39	16	51	26	74	40
22	26	–3	47	21	16	1	48	32	79	42
23	25	1	52	27	33	–6	55	31	77	44
24	21	–2	46	28	22	5	54	24	71	49
25	31	10	47	19	31	9	64	27	63	54
26	25	9	20	8	50	31	79	34	78	56
27	23	–1	13	0	39	32	85	48	78	52
28	24	–14	28	1	39	30	86	47	75	59
29	31	9	48	28	48	24	85	47	73	54
30	34	24			62	31	52	40	72	53
31	34	28			56	28			67	46

Appendix A: Table 3
(continued)

Wauseon, Ohio
1889
data source: Smith, 1915

Daily Temperature Extremes (°F)

day of	January		February		March		April		May	
month	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	39	23	26	2	33	29	40	30	62	26
2	43	24	35	23	35	32	56	34	45	33
3	48	28	32	22	49	28	52	36	64	32
4	45	24	40	21	35	26	45	31	74	35
5	36	30	40	8	46	32	41	26	78	42
6	37	32	18	0	46	28	48	19	84	49
7	33	30	20	8	40	30	58	23	87	58
8	39	32	35	17	36	15	64	26	88	59
9	44	27	29	7	30	23	60	41	87	61
10	28	18	35	5	37	26	68	33	91	64
11	31	20	34	16	47	19	58	36	83	56
12	34	14	22	2	56	34	67	41	78	50
13	38	27	22	–13	57	29	52	32	69	52
14	30	26	32	13	52	28	50	25	78	51
15	34	26	31	14	69	31	56	32	74	42
16	55	34	51	30	66	31	67	34	78	58
17	54	29	52	29	71	33	74	33	89	66
18	29	22	33	11	51	35	79	44	91	66
19	26	12	17	1	58	33	78	57	72	56
20	37	20	17	–2	42	29	76	49	74	47
21	26	10	44	0	48	32	64	44	56	39
22	41	1	36	1	58	29	58	33	55	36
23	48	22	9	–6	66	26	73	33	60	30
24	46	26	16	–7	67	30	72	51	72	43
25	49	19	25	–2	50	26	51	41	61	39
26	48	28	36	16	60	23	62	35	67	35
27	32	22	45	22	54	35	68	32	57	49
28	29	18	36	17	48	23	52	43	62	32
29	35	1			39	22	49	39	46	38
30	31	20			41	10	54	35	42	36
31	36	21			38	30			50	39

Appendix A: Table 3
(continued)

Wauseon, Ohio
1890
data source: Smith, 1915

day of month	Daily Temperature Extremes (° F)									
	January		February		March		April		May	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	54	35	37	27	24	16	46	21	60	40
2	56	32	41	28	28	14	60	23	66	33
3	36	25	52	39	33	18	58	38	77	47
4	44	24	64	38	33	13	56	35	66	47
5	58	41	62	29	22	5	55	28	54	41
6	58	29	34	21	27	0	63	33	49	34
7	33	28	30	23	25	5	60	44	57	29
8	34	26	28	18	34	6	76	44	61	28
9	42	20	32	5	45	9	62	39	58	48
10	45	37	43	13	37	32	43	28	59	37
11	66	38	50	14	56	36	62	26	59	31
12	64	38	39	27	53	39	76	53	69	37
13	64	19	46	22	50	33	75	56	62	53
14	32	14	42	36	38	26	63	41	65	45
15	37	31	45	25	28	11	48	36	65	46
16	33	12	53	28	34	9	57	29	62	40
17	29	6	60	34	42	28	63	28	60	44
18	38	16	53	28	49	27	61	32	74	43
19	48	24	33	23	43	28	50	22	57	44
20	53	23	38	17	54	29	62	26	58	44
21	26	9	25	15	61	43	71	24	57	41
22	22	1	38	15	46	33	78	40	79	49
23	30	16	36	28	44	22	71	56	78	62
24	25	12	61	34	46	28	60	40	82	59
25	44	17	45	39	59	39	54	30	74	59
26	49	36	50	31	44	28	48	40	72	49
27	46	30	41	30	42	21	62	40	74	44
28	42	19	38	20	36	25	65	30	78	46
29	44	26			41	23	68	43	85	59
30	50	29			38	24	70	35	88	56
31	55	37			43	23			77	61

Appendix A: Table 3
(continued)

Wauseon, Ohio
1891
data source: Smith, 1915

day of month	Daily Temperature Extremes (°F)									
	January		February		March		April		May	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	53	42	42	31	23	-4	51	39	70	39
2	47	17	46	27	29	10	55	36	67	41
3	25	5	47	9	28	19	42	32	64	39
4	27	9	14	0	29	12	36	25	53	37
5	30	23	39	8	37	-3	40	20	52	28
6	32	12	50	30	24	16	40	28	59	31
7	30	4	37	29	33	21	48	23	68	32
8	30	3	38	31	41	26	51	23	75	42
9	32	18	42	26	36	26	40	30	81	49
10	33	27	30	19	46	16	69	39	84	55
11	34	29	41	18	54	37	50	39	65	45
12	33	25	49	24	46	26	60	37	68	38
13	26	17	47	26	34	17	74	39	74	35
14	36	14	40	22	24	5	72	52	75	38
15	36	10	56	22	37	0	52	42	82	38
16	26	20	52	44	42	20	60	43	63	38
17	28	21	53	35	44	17	79	39	67	28
18	28	24	43	21	62	30	75	57	76	33
19	34	24	32	19	32	27	74	51	82	37
20	41	22	50	30	41	28	66	44	78	58
21	39	33	50	31	36	31	81	46	80	63
22	38	30	33	24	46	32	78	60	66	45
23	38	27	49	24	51	30	67	48	64	42
24	31	25	55	44	44	33	61	41	74	37
25	39	18	57	25	44	28	66	33	74	47
26	37	23	30	15	35	29	74	34	64	46
27	48	22	27	10	37	32	74	48	66	34
28	36	25	27	1	47	30	65	44	67	42
29	46	32			58	23	71	32	59	51
30	40	29			48	35	79	50	77	53
31	44	29			50	40			85	49

Appendix A: Table 3
(continued)

Wauseon, Ohio
1892
data source: Smith, 1915

day of month	Daily Temperature Extremes (° F)									
	January		February		March		April		May	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	55	39	45	32	33	21	74	42	67	48
2	51	18	40	33	37	13	72	55	72	58
3	26	11	36	30	47	19	63	43	75	57
4	27	16	37	29	40	33	70	54	66	52
5	33	–2	34	22	39	28	70	46	59	48
6	28	8	38	16	41	23	57	39	67	46
7	22	2	54	29	48	34	64	40	58	41
8	20	7	36	30	39	31	53	32	56	32
9	12	–7	30	18	54	28	33	24	61	37
10	17	–12	35	17	28	11	39	26	67	49
11	30	12	34	15	30	11	47	20	55	45
12	30	19	28	3	50	25	52	22	56	40
13	22	14	32	6	33	20	52	23	60	39
14	27	12	40	22	29	6	37	31	58	52
15	21	–10	25	9	33	11	52	22	69	55
16	25	–4	26	5	34	12	54	27	71	45
17	34	14	36	5	26	16	48	39	75	47
18	26	13	42	31	29	14	50	32	71	57
19	20	–8	35	31	32	21	50	30	62	44
20	15	–23	35	30	35	17	51	32	61	43
21	27	7	37	31	39	11	62	41	64	39
22	36	13	43	32	46	26	52	40	53	42
23	30	19	41	30	41	29	67	34	65	42
24	41	19	55	28	51	26	51	31	69	43
25	43	22	45	35	60	27	47	26	71	54
26	29	0	49	27	61	31	58	30	62	49
27	22	–9	32	24	51	35	77	40	65	43
28	38	15	45	25	53	26	71	49	69	38
29	42	31	39	32	57	25	60	37	74	56
30	36	24			47	37	64	33	81	54
31	39	18			58	40			83	64

Appendix A: Table 3
(continued)

Wauseon, Ohio
1893
data source: Smith, 1915

Daily Temperature Extremes (° F)

day of	January		February		March		April		May	
month	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	34	30	37	22	39	23	65	38	68	44
2	31	15	23	11	46	18	58	23	54	42
3	17	1	34	9	38	16	73	45	57	36
4	15	–5	20	–9	24	12	65	41	52	41
5	22	–10	39	7	32	14	71	31	55	37
6	25	4	43	30	45	15	56	30	65	35
7	27	–1	30	0	52	34	82	36	59	34
8	22	0	14	–5	50	29	73	42	65	33
9	26	5	37	12	58	35	61	32	71	45
10	9	–9	39	27	54	30	53	37	80	41
11	5	–13	34	25	58	38	53	33	83	52
12	20	–1	40	9	42	33	74	49	71	53
13	14	–7	37	21	61	31	66	40	56	49
14	9	–13	41	27	54	20	43	33	69	47
15	–1	–15	41	27	25	15	49	29	66	47
16	7	–6	35	21	30	6	57	29	54	44
17	9	–14	22	15	36	22	59	36	61	43
18	28	–1	31	13	38	15	54	40	69	41
19	26	–9	35	6	38	25	46	39	77	35
20	21	–5	16	–8	49	22	55	38	87	53
21	28	9	19	1	50	35	44	32	76	50
22	29	21	34	9	40	31	38	32	87	50
23	34	24	33	18	69	31	45	30	76	41
24	29	19	36	23	64	34	52	36	73	39
25	33	14	31	12	36	29	46	38	74	53
26	31	6	39	3	36	24	61	38	55	46
27	22	12	48	22	48	21	61	40	66	47
28	49	20	43	27	40	23	64	37	63	40
29	45	15			48	16	49	39	74	45
30	27	11			60	40	44	38	77	46
31	34	21			67	32			76	51

Appendix A: Table 3
(continued)

Wauseon, Ohio
1894
data source: Smith, 1915

Daily Temperature Extremes (° F)

day of month	January		February		March		April		May	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	41	20	31	15	50	31	48	31	74	62
2	51	34	35	6	52	34	48	23	68	57
3	50	37	36	29	58	30	60	28	80	37
4	52	35	27	12	67	38	60	42	74	54
5	57	33	37	2	70	54	41	35	66	52
6	36	28	50	23	60	34	56	25	75	55
7	26	17	43	36	43	24	58	36	68	47
8	35	11	42	36	47	32	51	25	68	45
9	36	20	58	35	53	26	43	26	79	41
10	40	16	44	30	67	34	43	37	85	52
11	36	26	35	24	61	36	47	34	69	44
12	25	16	25	17	57	27	59	30	79	40
13	48	12	29	12	57	37	67	28	80	47
14	48	31	27	2	47	27	65	44	85	48
15	46	40	30	6	56	30	68	41	66	48
16	44	38	23	6	62	32	78	35	84	53
17	51	34	37	18	76	38	76	41	87	67
18	53	34	39	23	78	52	79	43	72	39
19	42	18	38	19	67	48	71	56	40	33
20	56	29	15	12	50	39	62	44	48	38
21	50	33	18	6	71	40	51	38	55	44
22	38	25	26	0	59	41	47	38	51	40
23	31	20	24	9	51	35	53	42	62	46
24	32	0	11	–7	47	31	66	40	70	38
25	22	–6	32	–3	34	22	68	33	76	48
26	30	5	41	8	26	6	72	36	81	54
27	24	5	46	20	34	12	78	43	79	46
28	37	4	51	29	33	23	85	58	61	33
29	35	26			40	22	67	49	66	38
30	32	18			50	18	85	43	58	37
31	35	18			58	37			65	34

Appendix A: Table 3
(continued)

Wauseon, Ohio
1895
data source: Smith, 1915

Daily Temperature Extremes (°F)

day of month	January		February		March		April		May	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	32	10	28	5	52	29	39	33	76	50
2	35	6	21	–11	34	14	46	29	83	53
3	33	24	28	–3	48	21	49	22	88	57
4	22	8	15	3	18	1	55	30	92	58
5	23	11	13	–16	29	–2	67	32	94	62
6	43	28	2	–4	36	7	75	44	77	62
7	37	31	6	–7	42	21	59	45	78	61
8	32	20	3	–4	40	23	57	45	77	59
9	28	5	19	–5	41	15	57	38	86	55
10	31	21	20	–2	40	25	54	31	88	61
11	32	19	21	–3	28	15	58	26	74	43
12	19	–8	21	–11	39	23	58	37	55	31
13	17	–4	26	6	38	24	62	37	50	31
14	16	–1	32	19	24	5	52	35	44	33
15	32	11	36	5	20	9	60	33	50	29
16	36	13	36	2	30	12	50	38	61	33
17	28	14	34	12	39	18	57	36	65	33
18	39	2	32	28	51	26	60	36	72	44
19	31	25	35	20	43	21	72	32	63	48
20	43	15	35	14	38	25	75	35	52	38
21	50	29	36	26	44	16	76	40	60	30
22	24	17	29	9	44	19	64	35	70	31
23	18	12	31	15	60	23	65	40	77	40
24	18	6	43	13	63	37	82	38	82	45
25	25	4	47	33	54	38	85	51	78	49
26	36	18	45	21	38	29	66	45	69	47
27	12	–1	43	32	67	25	62	47	63	41
28	7	–9	61	41	55	28	69	41	88	44
29	20	–3			60	31	83	44	95	58
30	14	0			41	31	82	48	96	68
31	23	–11			42	31			96	70

Appendix A: Table 3
(continued)

Wauseon, Ohio
1896
data source: Smith, 1915

day	Daily Temperature Extremes (°F)									
of	January		February		March		April		May	
month	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	27	5	46	34	29	24	57	35	81	52
2	35	24	37	31	34	21	35	19	76	58
3	24	–1	33	30	34	19	38	20	78	49
4	3	–10	34	30	34	17	38	21	82	53
5	17	–8	41	25	37	16	57	21	77	53
6	19	5	41	30	50	29	49	31	77	50
7	36	11	33	27	38	27	45	22	79	48
8	28	11	34	27	36	26	50	26	90	52
9	36	26	31	24	39	19	48	33	91	57
10	38	29	39	19	36	25	53	32	92	63
11	37	27	32	20	26	14	81	46	90	64
12	37	17	26	12	24	1	85	41	87	56
13	22	13	31	19	26	0	78	58	83	60
14	26	18	31	16	32	1	74	55	80	59
15	26	3	45	21	37	20	82	51	76	50
16	35	3	21	3	36	17	89	61	80	50
17	42	20	19	–3	41	13	88	63	77	60
18	36	32	29	5	40	29	85	59	76	58
19	34	25	20	3	33	26	74	55	65	54
20	35	24	15	–6	34	13	66	41	68	43
21	31	21	19	–1	43	15	67	44	76	51
22	31	25	37	7	41	26	61	33	80	56
23	37	28	39	34	32	21	61	39	72	50
24	36	33	42	31	36	18	75	47	86	52
25	37	33	33	16	57	29	75	45	84	64
26	33	24	50	30	52	25	76	48	76	59
27	36	18	64	34	40	17	75	54	83	50
28	30	21	48	34	57	27	82	56	68	55
29	46	25	37	27	65	50	74	56	72	44
30	52	31			64	37	72	52	72	52
31	38	32			66	33			71	45

Appendix A: Table 3
(continued)

Wauseon, Ohio
1897
data source: Smith, 1915

Daily Temperature Extremes (°F)

day of month	January		February		March		April		May	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	53	38	28	4	41	19	52	34	44	37
2	56	51	37	25	36	20	57	30	44	35
3	57	49	36	27	45	25	60	31	51	41
4	58	26	32	21	39	21	64	39	67	45
5	28	15	36	24	54	33	54	45	77	44
6	23	12	37	34	37	26	46	40	80	50
7	26	7	35	32	35	18	41	36	69	47
8	39	20	36	29	45	25	46	29	78	44
9	41	22	30	27	62	48	41	31	83	52
10	36	30	31	24	51	35	49	28	76	53
11	30	25	31	24	55	30	40	33	76	45
12	26	13	34	21	48	27	49	22	72	56
13	26	15	34	24	32	17	60	40	69	50
14	29	24	38	28	35	27	51	38	57	48
15	30	15	35	22	41	17	59	32	66	37
16	35	31	41	25	40	18	48	37	70	37
17	54	36	46	37	41	24	51	32	73	42
18	33	21	40	28	65	40	65	33	79	48
19	27	12	42	17	49	40	57	31	79	51
20	33	11	44	31	58	49	48	16	72	63
21	33	26	41	29	61	35	62	30	63	47
22	35	15	41	30	60	39	76	51	71	39
23	13	5	35	26	43	32	77	51	67	53
24	12	–3	35	12	37	30	81	52	60	45
25	–2	–21	31	21	38	26	67	52	64	38
26	5	–20	24	12	43	19	63	43	67	36
27	8	–6	18	1	44	12	60	29	78	37
28	12	–4	29	12	50	22	79	38	60	49
29	19	7			64	28	66	55	69	45
30	31	10			64	33	56	47	61	46
31	31	–6			54	37			64	33

Appendix A: Table 3
(continued)

Wauseon, Ohio
1898
data source: Smith, 1915

day	Daily Temperature Extremes (° F)									
of	January		February		March		April		May	
month	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	19	9	14	–3	30	17	48	23	83	52
2	19	7	20	–3	36	22	44	28	76	57
3	35	21	14	–8	43	9	45	17	62	50
4	37	16	34	10	40	20	42	22	48	42
5	41	17	36	26	38	13	38	16	45	39
6	37	29	35	6	47	22	38	20	54	34
7	35	21	46	23	56	26	55	22	69	40
8	42	30	51	36	62	28	61	23	72	44
9	34	21	48	39	66	39	54	43	75	36
10	37	32	61	41	57	46	60	40	62	55
11	38	30	58	42	53	49	70	35	73	46
12	64	34	44	32	53	40	72	34	65	50
13	34	31	42	32	59	35	69	40	70	38
14	35	31	39	29	53	30	67	42	75	41
15	33	31	33	18	50	33	70	42	67	53
16	34	18	31	3	71	38	74	36	72	56
17	34	14	41	15	56	38	80	54	68	40
18	42	12	43	33	51	33	51	41	70	45
19	37	20	31	28	70	41	59	40	71	61
20	44	34	33	31	52	33	50	37	79	61
21	36	31	31	21	59	42	63	33	81	60
22	36	31	30	20	66	51	59	48	76	62
23	41	29	34	22	63	31	57	46	78	60
24	38	18	27	13	46	23	59	42	82	57
25	33	28	29	11	55	27	49	42	75	54
26	32	20	38	7	60	37	60	40	77	45
27	30	17	34	21	65	54	63	31	81	47
28	39	10	36	23	65	35	62	33	76	60
29	33	23			50	30	68	43	72	54
30	29	17			39	26	70	37	71	50
31	30	12			45	24			76	41

Appendix A: Table 3
(continued)

Wauseon, Ohio
1899
data source: Smith, 1915

Daily Temperature Extremes (° F)

day of	January		February		March		April		May	
month	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	23	3	19	−8	39	19	31	19	85	63
2	34	10	32	6	47	29	33	21	87	58
3	43	23	27	16	50	35	41	15	71	55
4	53	43	26	16	37	32	45	23	67	51
5	38	18	24	10	36	26	46	21	72	52
6	28	21	19	4	25	14	46	29	73	49
7	20	6	17	1	30	8	40	34	71	45
8	38	5	9	−6	29	6	44	31	69	51
9	32	20	−2	−17	45	17	50	26	78	44
10	20	7	2	−16	45	27	60	29	75	50
11	22	9	8	−10	66	36	71	40	73	53
12	36	15	7	−15	58	29	75	46	79	49
13	44	35	16	−17	31	25	81	45	66	54
14	41	35	21	−1	32	23	69	52	66	42
15	41	31	42	16	52	32	58	34	64	46
16	48	36	49	19	39	29	55	32	85	50
17	37	30	53	28	49	30	71	42	76	53
18	30	19	39	31	50	32	75	46	65	53
19	32	13	46	28	33	23	69	44	61	39
20	35	21	53	36	33	18	80	43	65	36
21	41	30	45	35	36	22	85	47	65	40
22	38	24	40	33	50	34	77	47	64	38
23	50	32	33	27	32	24	65	50	68	41
24	37	27	33	19	38	20	79	50	77	45
25	36	20	39	23	41	30	75	55	81	47
26	41	18	62	34	39	26	84	50	80	54
27	17	4	34	23	41	27	85	56	77	62
28	24	4	44	24	32	26	86	66	79	65
29	14	−7			36	15	91	60	76	61
30	13	−1			31	23	90	68	81	56
31	12	−13			39	23			81	59

Appendix A: Table 3
(continued)

Wauseon, Ohio
1912
data source: Smith, 1915

Daily Temperature Extremes (° F)

day of	January		February		March		April		May	
month	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	28	16	30	5	20	6	38	31	60	39
2	26	14	20	0	21	2	35	32	73	40
3	23	8	10	–14	18	10	43	26	73	49
4	16	1	3	–11	23	7	64	28	76	46
5	5	–6	16	–2	22	7	71	37	77	47
6	4	–5	24	4	30	9	74	50	81	55
7	5	–9	24	13	37	15	40	40	82	52
8	20	–2	16	–1	35	27	54	28	72	53
9	6	–4	14	–7	27	12	68	32	65	42
10	12	–3	7	–18	30	13	59	33	76	38
11	10	–3	19	–2	30	16	74	39	75	54
12	9	–2	18	–5	32	28	69	41	65	55
13	12	–19	24	–12	35	14	46	40	58	32
14	19	6	35	10	40	23	74	40	60	38
15	16	–1	37	26	33	9	78	45	63	36
16	19	–4	31	17	36	3	63	39	57	46
17	35	10	38	26	49	20	41	33	65	44
18	39	22	48	22	45	31	41	34	73	45
19	22	5	41	31	49	35	52	30	66	45
20	21	1	36	23	38	19	56	31	83	46
21	26	8	27	16	28	20	70	40	83	58
22	35	24	23	10	29	15	59	48	86	52
23	36	22	37	11	36	18	59	29	89	63
24	23	13	43	29	33	22	62	37	77	66
25	22	15	41	29	33	11	67	29	76	48
26	23	15	44	25	43	25	67	46	83	51
27	21	1	25	16	40	26	59	43	86	62
28	23	1	29	17	37	27	45	36	72	65
29	28	22	23	10	43	29	44	39	62	56
30	26	17			43	23	61	36	72	50
31	27	8			62	33			79	45

Appendix A: Table 3
(continued)

Cream Hill, Connecticut
1937
data source: U.S. Weather Bureau, 1937a

day	Daily Temperature Extremes (° F)									
of	January		February		March		April		May	
month	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	50	28	39	26	40	14	49	26	75	37
2	32	24	26	8	40	25	40	32	72	42
3	43	29	22	3	39	21	44	25	80	42
4	38	19	34	5	56	30	42	26	79	52
5	42	22	36	16	49	27	41	32	75	52
6	30	13	35	19	27	19	66	38	69	54
7	37	16	32	20	28	8	54	32	71	49
8	58	32	30	22	34	14	52	31	65	44
9	57	43	46	30	34	22	46	31	73	45
10	47	23	37	22	22	8	36	27	64	40
11	28	9	25	12	32	11	42	27	68	32
12	37	17	45	15	39	12	52	29	73	45
13	39	22	54	34	35	24	62	32	64	53
14	46	32	45	30	35	16	66	44	62	50
15	60	35	34	22	30	24	62	51	51	42
16	35	21	35	21	30	24	58	44	64	35
17	31	10	33	11	34	20	62	30	61	46
18	46	27	42	17	42	29	64	38	65	45
19	44	26	56	24	40	30	65	42	58	45
20	26	16	52	33	36	26	57	39	56	39
21	42	16	44	35	36	31	48	34	69	44
22	42	33	46	27	35	26	40	32	78	52
23	33	22	39	21	38	20	49	30	78	57
24	32	11	37	24	41	19	60	30	66	47
25	46	30	36	23	38	28	60	29	77	45
26	37	26	34	15	28	15	61	32	77	57
27	28	15	32	23	36	19	50	37	76	54
28	34	11	34	9	36	19	60	42	71	58
29	43	22			40	20	60	40	80	57
30	46	19			40	21	69	34	84	53
31	34	26			48	18			86	56

Appendix A: Table 3
(continued)

Cream Hill, Connecticut
1938
data source: U.S. Weather Bureau, 1938

day of month	Daily Temperature Extremes (° F) January Max	January Min	February Max	February Min	March Max	March Min	April Max	April Min	May Max	May Min
1	28	13	20	11	34	0	62	42	65	38
2	36	18	28	5	47	34	49	28	70	47
3	31	20	38	22	40	10	42	25	64	45
4	30	18	38	30	30	–2	41	25	73	40
5	38	21	41	20	36	18	38	25	74	48
6	48	24	48	30	44	26	35	15	71	55
7	44	36	46	30	37	19	46	24	64	42
8	36	20	36	15	34	26	39	25	58	44
9	24	7	45	28	35	16	38	30	65	43
10	21	10	38	24	38	18	38	27	59	45
11	24	10	28	7	43	18	53	20	57	37
12	21	11	32	20	44	28	67	35	53	35
13	34	19	38	32	55	31	69	40	54	32
14	30	20	42	30	47	34	78	48	64	37
15	26	10	30	10	54	20	74	58	48	38
16	26	4	23	7	40	28	69	42	62	38
17	26	20	38	11	35	32	67	34	69	44
18	20	–9	49	28	50	30	54	44	69	45
19	25	–8	45	31	55	35	66	51	65	39
20	35	14	35	23	54	40	82	50	56	49
21	36	18	41	5	65	44	73	47	67	48
22	32	24	33	17	77	44	64	44	73	50
23	40	23	40	27	76	54	60	30	67	50
24	38	30	34	26	63	42	63	35	68	53
25	55	38	31	22	57	27	63	35	69	37
26	40	18	32	9	46	34	69	40	68	46
27	21	10	33	20	42	32	75	45	69	41
28	20	3	21	–1	50	24	85	55	79	51
29	24	6			66	38	78	58	66	53
30	51	22			54	34	58	42	67	39
31	49	23			47	36			74	34

Appendix A: Table 3
(continued)

Cream Hill, Connecticut
1939
data source: U.S. Weather Bureau, 1939

Daily Temperature Extremes (°F)

day of month	January		February		March		April		May	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	30	20	30	4	41	32	53	29	58	35
2	44	22	31	16	32	18	43	29	57	34
3	32	16	37	29	40	14	37	26	51	38
4	28	14	29	20	40	27	33	25	64	41
5	28	23	32	9	43	37	47	25	68	45
6	45	27	41	22	53	39	44	30	80	47
7	43	32	32	24	39	22	44	27	84	58
8	38	30	41	20	29	8	36	22	78	47
9	44	26	38	25	28	19	38	25	67	46
10	50	34	31	19	32	14	37	24	75	52
11	46	32	38	20	24	–1	61	32	70	52
12	34	20	29	5	27	14	48	30	59	38
13	28	15	46	27	30	23	43	20	47	34
14	20	15	40	25	37	23	48	28	64	33
15	30	10	55	34	34	22	46	35	63	38
16	40	15	34	5	39	27	53	28	64	35
17	32	21	25	–3	31	15	52	29	69	35
18	25	13	43	22	28	11	43	30	64	45
19	28	12	42	29	25	7	53	43	77	40
20	22	6	59	39	38	16	50	36	80	60
21	25	10	44	25	34	14	63	35	75	57
22	40	15	33	12	31	15	60	45	66	51
23	23	–2	22	3	37	12	62	38	60	49
24	34	12	38	11	58	32	62	38	74	46
25	34	4	35	14	58	35	82	47	78	47
26	10	–4	36	25	59	33	72	44	74	55
27	18	–4	45	32	52	40	61	45	78	53
28	25	6	36	24	40	28	58	36	83	64
29	34	23			44	18	57	35	82	62
30	33	19			40	28	61	33	78	53
31	21	14			42	35			87	63

Appendix A: Table 3
(continued)

Wisconsin Dells, Wisconsin
1936
data source: U.S. Weather Bureau, 1936

day of month	Daily Temperature Extremes (° F) January Max	Min	February Max	Min	March Max	Min	April Max	Min	May Max	Min
1	40	25	–7	–23	33	15	29	19	74	54
2	34	29	10	–30	39	24	32	20	56	38
3	33	29	13	2	50	27	32	15	58	36
4	33	11	13	–19	41	17	30	9	72	34
5	30	2	–2	–26	24	1	31	26	75	45
6	32	14	3	–30	21	–2	38	11	87	59
7	24	6	12	–10	38	18	30	12	82	63
8	31	15	27	–15	38	19	47	15	85	56
9	31	8	10	–17	44	30	55	34	88	55
10	27	–3	12	–6	61	36	53	33	83	53
11	34	8	10	–21	39	30	61	38	79	57
12	38	20	6	–6	32	18	57	30	78	52
13	26	11	20	0	35	12	56	26	64	39
14	39	17	19	–12	33	22	67	35	69	34
15	29	–3	2	–12	38	25	62	36	76	46
16	24	–6	4	–25	46	22	48	33	90	44
17	20	–6	–2	–18	44	21	51	29	81	56
18	22	–13	1	–28	30	17	52	21	73	48
19	18	–18	11	–20	40	26	71	27	69	43
20	7	–22	20	–16	58	28	58	30	56	38
21	14	–11	20	–28	56	25	47	25	81	44
22	–4	–29	22	–33	48	28	55	16	87	58
23	–10	–27	40	8	72	41	60	19	79	61
24	–4	–31	47	25	59	33	50	32	74	52
25	3	–34	39	26	49	28	58	36	84	49
26	–1	–21	31	9	48	31	62	25	81	54
27	7	–11	26	5	48	26	54	39	83	43
28	15	–20	31	–6	67	23	73	49	78	42
29	19	–13	33	10	48	24	67	38	77	39
30	7	–13			27	16	64	35	79	39
31	2	–17			29	13			84	47

Appendix A: Table 3
(continued)

Wisconsin Dells, Wisconsin
1937
data source: U.S. Weather Bureau, 1937b

Daily Temperature Extremes (°F)

day of	January		February		March		April		May	
month	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	24	10	15	–8	39	15	42	30	70	45
2	36	20	16	–16	46	18	46	30	67	51
3	25	1	29	–6	45	15	37	30	68	50
4	37	1	25	1	48	15	41	33	68	47
5	11	5	28	–9	51	30	44	32	63	43
6	34	10	28	3	58	28	55	24	71	35
7	33	11	29	3	38	32	40	33	73	35
8	25	–1	31	5	33	15	54	33	70	42
9	5	–11	14	–6	24	4	54	25	62	39
10	20	–18	16	–15	31	10	53	21	70	31
11	30	1	39	5	35	14	60	20	66	54
12	31	8	43	26	36	18	50	27	76	56
13	38	13	38	23	29	20	65	38	58	42
14	38	10	23	16	34	20	61	37	69	33
15	12	–6	26	15	33	19	43	31	58	32
16	27	–10	38	6	46	14	51	28	68	48
17	32	15	37	5	46	16	60	42	74	46
18	32	–3	44	32	46	29	69	41	67	45
19	12	–15	40	33	46	22	73	39	70	36
20	37	11	39	34	42	25	57	39	58	45
21	19	–5	34	5	44	25	45	34	79	49
22	8	–19	14	–3	42	20	60	32	69	50
23	18	–28	19	7	42	12	65	35	70	50
24	23	–11	16	6	34	13	59	39	73	47
25	23	–4	30	6	18	1	42	35	76	56
26	14	–16	28	15	10	0	49	38	69	56
27	35	–7	29	6	39	3	45	35	69	51
28	32	10	25	–2	43	16	55	31	80	49
29	28	4			55	12	62	42	82	60
30	37	18			49	12	51	48	96	68
31	18	–1			48	28			87	64

Appendix A: Table 3
(continued)

Wisconsin Dells, Wisconsin
1944
data source: U.S. Weather Bureau, 1944

Daily Temperature Extremes (°F)

day of month	January Max	January Min	February Max	February Min	March Max	March Min	April Max	April Min	May Max	May Min
1	40	18	40	10	38	17	41	25	78	54
2	44	15	49	25	44	28	39	19	70	48
3	45	12	51	23	45	33	35	18	74	48
4	35	13	47	17	33	25	36	16	50	37
5	31	12	46	14	34	15	53	21	59	29
6	26	1	35	2	33	18	62	22	54	30
7	22	–4	35	15	21	13	61	26	60	40
8	21	–12	39	19	22	15	68	28	51	45
9	26	–1	30	10	24	–4	59	36	56	44
10	40	8	18	14	42	–7	52	28	67	33
11	23	1	17	5	48	33	41	35	83	57
12	19	–3	22	–4	33	17	63	25	81	59
13	30	–4	26	0	30	13	66	25	74	52
14	38	15	33	21	33	29	44	32	83	48
15	35	9	26	6	32	29	33	29	83	56
16	35	22	27	6	36	28	46	27	88	62
17	44	15	29	1	34	25	54	23	82	58
18	47	32	25	–4	27	14	59	30	68	46
19	46	25	31	–3	33	12	68	26	71	42
20	42	11	37	11	44	12	55	40	82	47
21	50	25	41	10	45	15	50	40	60	54
22	53	23	43	33	39	30	48	40	78	54
23	43	11	40	25	52	34	54	45	76	58
24	42	20	44	15	60	30	63	43	75	59
25	62	40	41	29	41	20	47	41	84	64
26	63	45	48	32	35	15	55	39	80	63
27	45	36	41	25	46	22	62	29	85	62
28	45	30	36	20	38	13	65	24	86	53
29	49	21	42	11	31	21	70	29	89	60
30	41	18			34	19	69	47	91	64
31	39	21			40	18			90	66

Appendix A: Table 3
(continued)

Madison, Wisconsin
1959
data source: U.S. Weather Bureau, 1959

day of month	Daily Average Temperature (° F)				
	January	February	March	April	May
1	28	–7	30	38	58
2	15	–7	36	46	74
3	–2	22	28	39	72
4	–7	10	26	45	76
5	–1	6	28	48	79
6	7	0	24	45	64
7	17	24	16	54	53
8	15	13	32	42	51
9	13	25	26	37	54
10	12	16	20	37	69
11	18	8	29	38	62
12	22	26	25	39	62
13	28	24	24	45	49
14	34	31	25	50	47
15	15	17	26	58	48
16	4	26	22	58	56
17	1	19	16	62	65
18	8	7	20	48	61
19	6	–1	44	38	69
20	3	6	39	38	70
21	8	26	20	42	71
22	1	27	21	49	52
23	–7	28	42	53	53
24	14	17	44	43	55
25	6	19	36	50	63
26	4	25	34	44	73
27	4	24	32	41	73
28	22	32	31	53	72
29	32		35	57	72
30	16		37	56	65
31	–5		49		70

Appendix A: Table 3
(continued)

Ann Arbor, Michigan
1967
data source: U.S. Environmental Data Service, 1967

day of month	Daily Temperature Extremes (°F) January Max	January Min	February Max	February Min	March Max	March Min	April Max	April Min	May Max	May Min
1	33	31	34	23	23	2	69	56	74	58
2	33	26	34	23	44	18	76	56	73	48
3	34	25	24	12	43	30	71	28	54	33
4	34	18	36	22	40	21	50	24	53	37
5	31	13	36	21	32	25	65	46	55	40
6	30	19	23	9	36	26	62	46	56	42
7	41	28	18	–3	35	19	46	35	59	44
8	30	28	16	4	25	7	55	32	58	43
9	29	17	31	15	36	14	70	44	75	50
10	29	22	38	23	57	32	70	36	59	36
11	26	21	37	17	51	42	49	27	58	47
12	38	26	17	–1	44	26	49	24	62	39
13	41	29	26	12	49	32	56	39	67	45
14	38	28	48	26	47	32	69	53	66	48
15	35	20	47	36	43	28	69	52	57	44
16	23	8	46	8	34	15	67	53	61	36
17	23	15	28	14	27	8	74	52	69	45
18	15	–5	28	13	26	7	52	38	75	47
19	21	–6	35	21	37	15	59	34	75	60
20	38	17	35	26	36	31	57	35	67	40
21	43	30	26	17	36	32	65	46	62	42
22	46	32	34	18	40	30	65	37	65	41
23	59	46	33	13	40	32	48	33	61	40
24	58	45	18	2	44	29	45	31	76	49
25	59	33	15	1	59	33	54	27	79	53
26	33	29	24	3	71	39	51	41	72	55
27	31	26	32	18	66	49	55	32	82	54
28	32	26	32	20	54	40	63	37	75	53
29	30	16			58	34	65	43	71	52
30	35	14			65	36	68	50	70	49
31	34	15			72	53			69	48

Appendix A: Table 3
(continued)

Asheville, North Carolina
1972
data source: U.S. Environmental Data Service, 1972

day of month	Daily Average Temperature (° F)				
	January	February	March	April	May
1	34	31	51	47	60
2	43	36	59	41	64
3	39	35	42	46	61
4	47	25	42	52	58
5	40	31	38	47	57
6	31	34	39	56	56
7	38	32	46	60	60
8	39	31	43	43	60
9	42	35	38	41	61
10	55	36	42	49	58
11	52	42	44	58	53
12	47	32	53	65	55
13	58	40	55	71	56
14	44	45	49	70	67
15	20	44	52	72	65
16	14	39	52	68	60
17	27	38	43	60	61
18	38	34	41	56	64
19	48	24	51	62	60
20	48	28	51	68	62
21	58	35	55	54	66
22	51	43	55	58	66
23	54	32	42	57	65
24	50	51	39	56	65
25	45	50	36	49	66
26	40	48	42	47	62
27	40	40	47	51	61
28	52	50	59	54	64
29	44	54	52	63	66
30	38		48	59	65
31	35		40		61

Appendix A: Table 3
(continued)

Asheville, North Carolina
1974
data source: U.S. Environmental Data Service, 1974

day of	Daily Average Temperature (° F)				
month	January	February	March	April	May
1	44	48	57	61	66
2	36	53	55	65	58
3	50	49	55	60	68
4	48	34	59	62	62
5	43	36	58	46	54
6	53	41	63	41	56
7	41	47	65	45	54
8	38	37	63	50	53
9	50	28	62	41	64
10	60	35	62	47	66
11	51	35	55	48	68
12	32	41	55	56	64
13	30	44	46	64	61
14	33	52	41	66	60
15	52	50	45	53	67
16	56	37	44	51	70
17	57	42	37	48	71
18	44	41	43	51	73
19	56	47	53	53	72
20	52	44	59	53	65
21	50	43	44	59	64
22	50	48	42	61	69
23	51	41	43	60	70
24	58	41	40	48	70
25	56	23	33	54	67
26	53	27	46	55	58
27	58	34	49	60	60
28	51	42	56	64	59
29	49		53	66	69
30	50		54	66	69
31	47		55		70

Appendix A: Table 3
(continued)

Asheville, North Carolina
1975
data source: U.S. Environmental Data Service, 1975

Daily Temperature Extremes (°F)

day of month	January		February		March		April		May	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	61	31	66	44	54	28	69	34	71	57
2	50	25	49	37	31	19	70	36	77	57
3	50	28	37	32	33	16	60	34	61	53
4	46	29	34	29	45	18	49	29	73	55
5	49	22	52	32	54	19	54	32	74	42
6	38	26	52	30	64	22	57	31	79	40
7	55	28	34	19	63	32	62	33	70	56
8	44	38	51	14	42	25	64	36	69	53
9	65	34	49	26	46	19	69	34	73	56
10	60	38	48	16	42	30	67	46	77	51
11	63	39	62	35	48	33	64	44	73	48
12	41	34	58	32	58	44	54	31	71	53
13	35	20	48	29	59	51	63	29	74	49
14	31	13	53	25	60	31	48	44	74	42
15	48	13	62	32	57	30	55	42	70	60
16	50	25	60	40	45	40	65	38	79	59
17	45	21	65	45	60	42	76	35	73	59
18	54	30	55	43	44	37	74	49	75	60
19	61	35	55	33	54	39	70	44	80	55
20	48	27	52	29	70	42	67	41	84	54
21	43	22	59	24	75	37	69	40	86	54
22	52	30	51	27	69	49	74	32	85	60
23	50	30	64	45	74	35	71	48	85	59
24	55	30	63	34	65	52	76	57	86	59
25	56	44	61	32	63	34	79	55	87	56
26	55	36	58	34	58	28	79	46	81	56
27	64	28	52	28	56	30	76	45	81	59
28	72	31	58	25	63	41	85	53	81	55
29	72	39			64	54	81	55	79	60
30	70	42			60	33	68	57	80	63
31	78	36			58	31			77	64

Appendix A: Table 3
(continued)

Columbia, Missouri
1976
data source: U.S. National Climatic Data Center, 1976

day of month	Daily Average Temperature (° F)				
	January	February	March	April	May
1	39	31	58	47	56
2	35	16	65	58	49
3	17	21	42	54	42
4	13	27	54	48	53
5	28	22	33	50	65
6	37	15	34	59	50
7	12	20	41	62	47
8	0	37	39	51	50
9	12	46	43	49	54
10	31	57	46	55	59
11	31	43	49	50	64
12	38	49	43	45	62
13	34	44	32	57	58
14	29	45	39	66	58
15	34	61	37	71	63
16	30	55	30	70	58
17	19	45	41	72	57
18	26	47	54	62	55
19	31	48	62	52	60
20	23	51	56	60	65
21	35	42	45	57	69
22	37	35	42	62	70
23	50	44	48	68	64
24	39	56	55	59	61
25	31	56	53	43	58
26	18	52	60	46	61
27	18	57	48	47	63
28	35	58	52	44	66
29	39	61	56	48	66
30	40		48	53	69
31	33		44		71

Appendix A: Table 3
(continued)

Ithaca, New York
1983
data source: U.S. National Climatic Data Center, 1983b

Daily Temperature Extremes (° F)

day of month	January Max	January Min	February Max	February Min	March Max	March Min	April Max	April Min	May Max	May Min
1	36	13	36	31	53	28	44	17	68	50
2	39	25	37	22	50	31	48	19	63	48
3	39	25	49	33	46	31	55	35	70	56
4	29	2	45	25	45	29	54	37	73	48
5	28	5	27	12	54	35	50	39	57	36
6	41	18	21	2	61	37	50	29	56	29
7	37	25	28	13	54	41	51	39	63	38
8	38	29	28	19	58	36	56	45	74	54
9	33	11	26	13	43	36	48	26	58	33
10	38	13	17	–15	46	37	60	35	45	34
11	44	30	15	–11	40	31	45	37	48	29
12	45	27	20	–2	35	26	44	37	56	30
13	28	11	21	–7	35	25	45	24	60	32
14	25	12	35	–6	45	23	60	40	68	36
15	33	24	45	15	54	29	55	45	79	49
16	32	20	36	29	45	32	52	31	67	42
17	22	12	44	31	49	27	42	27	47	26
18	21	6	43	32	52	34	47	30	52	26
19	8	1	36	20	53	40	38	26	64	41
20	12	1	48	22	57	37	33	25	60	50
21	14	–8	53	33	39	30	34	29	74	45
22	29	–6	57	31	47	28	43	25	71	45
23	34	4	45	32	31	14	53	24	67	57
24	38	32	43	28	28	18	61	36	76	46
25	37	33	39	24	29	9	44	31	60	35
26	38	17	33	17	31	9	39	31	74	44
27	23	13	26	10	42	23	59	33	60	32
28	29	15	46	15	40	30	70	41	56	30
29	34	11			42	24	80	48	66	33
30	44	15			31	18	60	46	63	50
31	39	32			36	15			76	

Appendix A: Table 4

Freezing Resistance of Temperate Forest Tree Species

Boreal Forest Species

		Freezing Temperature (°C)					location	
Species	type	bud	leaf	twig	xylem	cortex		Reference
Abies balsamea	KT				–54*		MN	George et al., 1974
Abies balsamea	FR	–40	–70	–70			WI	Sakai & Okada, 1971
Abies balsamea	FR	–55	–70*		–70*	–70*	Que.	Sakai, 1983
Abies balsamea	FR	–80*	–80*	–80*			WI	Sakai & Weiser, 1973
Alnus rugosa	KT				–54*		MN	George et al., 1974
Betula papyrifera	KT				–54*		MN	George et al., 1974
Larix laricina	KT				–54*		MN	George et al., 1974
Larix laricina	FR	–70*			–70*	–70*	AK	Sakai, 1983
Larix laricina	FR	–80*		–80*			WI	Sakai & Weiser, 1973
Larix laricina	FR	–120*					US	Sakai & Okada, 1971
Larix laricina	FR	–120*					Can.	Sakai & Okada, 1971
Picea glauca	FR	–50	–70*	–70*			N.S.	Sakai & Okada, 1971
Picea glauca	FR	–50	–80*	–80*			WI	Sakai & Weiser, 1973
Picea glauca	FR	–70*	–70*		–70*	–70*	AK	Sakai, 1983
Picea glauca	FR	–70*	–70*	–70*			AK	Sakai & Okada, 1971
Picea glauca	FR	–80*	–80*	–80*			AK	Sakai & Weiser, 1973
Picea mariana	FR	–50	–70*	–70*			NY	Sakai & Okada, 1971
Picea mariana	FR	–50	–80*	–80*			WI	Sakai & Weiser, 1973
Picea mariana	FR	–70*	–70*		–70*	–70*	AK	Sakai, 1983
Picea mariana	FR	–70*	–70*	–70*			AK	Sakai & Okada, 1971
Picea mariana	FR	–80*	–80*	–80*			AK	Sakai & Weiser, 1973
Picea rubens	FR	–35	–60	–60			NY	Sakai & Okada, 1971
Pinus banksiana	FR	–70*	–70*		–70*	–70*	Que.	Sakai, 1983
Pinus banksiana	FR	–80	–80*	–80*			WI	Sakai & Weiser, 1973
Pinus banksiana	FR	–90	–90	–90			NY	Sakai & Okada, 1971
Pinus resinosa	FR	–80*	–80*	–80*			WI	Sakai & Weiser, 1973
Pinus resinosa	FR	–90	–90	–90			WI	Sakai & Okada, 1971
Pinus strobus	KT				–54*		MN	George et al., 1974
Pinus strobus	FR	–80*	–80*	–80*			WI	Sakai & Weiser, 1973
Pinus strobus	FR	–90	–90	–90			WI	Sakai & Okada, 1971
Populus balsamifera	FR	–80*	–80*	–80*			WI	Sakai & Weiser, 1973
Populus tremuloides	KT				–54*		MN	George et al., 1974
Populus tremuloides	FR	–80*	–80*	–80*			WI	Sakai & Weiser, 1973
Thuja occidentalis	KT				–54*		MN	George et al., 1974
Thuja occidentalis	FR	–80*	–80*	–80*			MN	Sakai & Weiser, 1973
Thuja occidentalis	FR		–90	–90			US	Sakai & Okada, 1971
Tsuga canadensis	FR	–35	–70	–50			Can.	Sakai & Okada, 1971
Tsuga canadensis	FR	–60	–60	–60			WI	Sakai & Weiser, 1973

Appendix A: Table 4
(continued)

Eastern Deciduous Forest Species

		Freezing Temperature (°C)						
Species	type	bud	leaf	twig	xylem	cortex	location	Reference
Acer rubrum	KT				–54*		MN	George et al., 1974
Acer saccharum	KT				–43		MN	George et al., 1974
Acer saccharum	FR	–80			–40	–80	MN	Sakai & Weiser, 1973
Betula lutea	KT				–45		MN	George et al., 1974
Betula nigra	KT				–54*		MN	George et al., 1974
Betula nigra	FR	–60*			–60*	–60*	IN	Sakai & Weiser, 1973
Carya cordiformis	KT				–48		MN	George et al., 1974
Carya ovata	KT				–46		MN	George et al., 1974
Fagus grandifolia	FR	–30			–30	–30	IN	Sakai & Weiser, 1973
Fagus grandifolia	FR	–30			–30	–40	CT	Sakai & Weiser, 1973
Fagus grandifolia	KT				–41		MN	George et al., 1974
Fraxinus americana	KT				–46		MN	George et al., 1974
Fraxinus nigra	KT				–54*		MN	George et al., 1974
Fraxinus pennsylvanica	KT				–54		MN	George et al., 1974
Fraxinus pennsylvanica	KT			–50			Sask.	Gusta et al., 1983
Fraxinus pennsylvanica	FR	–40			–40	–70*	MN	Sakai & Weiser, 1973
Juglans cinerea	FR	–25			–50*	–50*	IN	Sakai & Weiser, 1973
Juglans cinerea	KT				–51		MN	George et al., 1974
Juglans nigra	FR	–30			–30	–80*	IN	Sakai & Weiser, 1973
Juglans nigra	KT				–43		MN	George et al., 1974
Nyssa sylvatica	FR	–30			–30	–50		Sakai & Weiser, 1973
Platanus occidentalis	FR	–30			–30	–30	IN	Sakai & Weiser, 1973
Platanus occidentalis	KT				–40		MN	George et al., 1974
Populus deltoides	FR	–80*			–80*	–80*	IN	Sakai & Weiser, 1973
Populus grandidentata	KT				–54*		MN	George et al., 1974
Prunus serotina	KT				–43		MN	George et al., 1974
Quercus alba	KT				–43		MN	George et al., 1974
Quercus coccinea	KT			–45			Sask.	Gusta et al., 1983
Quercus macrocarpa	KT				–46		MN	George et al., 1974
Quercus macrocarpa	KT			–47			Sask.	Gusta et al., 1983
Quercus macrocarpa	FR	–60*			–40	–60*	MN	Sakai & Weiser, 1973
Quercus rubra	KT				–40		MN	George et al., 1974
Salix nigra	FR	–80*			–80*	–80*	IN	Sakai & Weiser, 1973
Taxodium distichum	FR	–30			–30	–30	IN	Sakai & Weiser, 1973
Tilia americana	KT				–54*		MN	George et al., 1974
Tilia americana	FR	–80*			–80*	–80*	MN	Sakai & Weiser, 1973
Ulmus americana	KT			–50			Sask.	Gusta et al., 1983
Ulmus americana	KT				–54*		MN	George et al., 1974
Ulmus americana	FR	–80*			–40	–80*	MN	Sakai & Weiser, 1973

Appendix A: Table 4
(continued)

Southern Pine species

		Freezing Temperature (°C)					location	
Species	type	bud	leaf	twig	xylem	cortex		Reference
Pinus elliottii	FR	−20	−10	−10			Miss.	Sakai & Weiser, 1973
Pinus elliottii	FR	−25	−10	−10			Japan	Sakai & Weiser, 1973
Pinus elliotti	FR			−22			Japan	Oohata & Sakai, 1982
Pinus palustris	FR	−20	−15	−10			Japan	Sakai & Weiser, 1973
Pinus palustris	FR			−18			Japan	Oohata & Sakai, 1982
Pinus palustris	FR	−20	−18					Sakai, 1983
Pinus palustris	FR		−24				CT	Parker, 1963
Pinus taeda	FR	−25	−10	−20			Japan	Sakai & Weiser, 1973
Pinus taeda	FR			−23			Japan	Oohata & Sakai, 1982
Pinus taeda	FR	−25	−22					Sakai, 1983

Notes:
* indicates that tissue was uninjured at the lowest temperature at which it was tested.
FR indicates that the temperatures shown are the lowest at which there was no injury.
KT indicates that the temperatures shown are the temperatures at which the tissue was killed.

The locations given are those where the plant was growing at the time of testing.
Not shown are the original (native) locations for the plant material, which may also affect frost resistance temperatures.

Appendix A: Table 5
Soils Data: Summary of Locations

82° transect

Lat.	County	State	Survey ref.	Year	Most abundant soil type	Soil type used	Source
37.0	Russell	VA	not available	1945			
36.5	Sullivan	TN	not available	1953			
36.0	Avery	NC	not available	1955			
35.5	Rutherford	NC	not available	1924			
35.0	Spartanburg	SC	SCS	1968	Cecil Sandy Loam	same	
34.5	Laurens	SC	no survey				
34.0	Greenwood	SC	SCS	1980b	Cecil Sandy Loam	same	
33.5	Richmond	GA	SCS	1981	Troup Fine Sand	same	
33.0	Burke	GA	SCS	1986	Dothan Loamy Sand	same	
32.5	Candler	GA	SCS	1980a	Osier	same	
32.0	Tattnall	GA	SCS	1980a	Pelham Loamy Sand Tifton Loamy Sand	same	
31.5	Wayne	GA	SCS	1965	Plummer Soils Rutledge Sand	same	
31.0	Charlton	GA	no survey				
30.5	Nassau	FL	no survey				
30.0	Clay	FL	no survey				
29.5	Putnam	FL	Mooney et al.	1919	Norfolk Fine Sand	Troup Fine Sand	SCS 1981
						Pomona Fine Sand	SCS 1984a
						Immokalee Fine Sand	SCS 1984b
29.0	Marion	FL	SCS	1979c	Candler Sand	same	
28.5	Sumter	FL	no survey				
28.0	Polk	FL	not available	1927			
27.5	Hardee	FL	SCS	1984a	Pomona Fine Sand	same	
27.0	Charlotte	FL	not available	1985			
26.5	Lee	FL	SCS	1984b	Immokalee Fine Sand	same	

Appendix A: Table 5
(continued)

86° transect

Lat.	County	State	Survey ref.	Year	Most abundant soil type	Soil type used	Source
37.0	Barren	KY	SCS	1969	Baxter Cherty Silt Loam	same	
36.5	Macon	TN	no survey				
36.0	DeKalb	TN	SCS	1972	Bodine Cherty Silt Loam	same	
35.5	Coffee	TN	SCS	1959	Mountview Silt Loam	Mountview Silt Loam	SCS, 1972
35.0	Franklin	TN	SCS	1958b	Hartsells Fine Sandy Loam	Hartsells Fine Sandy Loam	SCS, 1978a (Chattooga)
						Hartsells Fine Sandy Loam	SCS, 1978b (Etowah)
34.5	DeKalb	AL	SCS	1958a	Hartsells Fine Sandy Loam	Hartsells Fine Sandy Loam	SCS, 1979a (Blount)
34.0	Etowah	AL	SCS	1978b	Hartsells Fine Sandy Loam	same	
33.5	Talladega	AL	Mooney & Mann	1909	Talladega Slate Loam	Louisa Slaty Loam	SCS, 1967
33.0	Tallapoosa	AL	Smith & Avary	1912	Cecil Stony Sandy Loam	Cecil Gravelly Sandy Loam	SCS, 1967
32.5	Elmore	AL	not available	1955			
32.0	Montgomery	AL	SCS	1960	Sumter Clay	no replacement found	
31.5	Coffee	AL	SCS	1979b	Luverne	same	
31.0	Geneva	AL	SCS	1977	Dothan Sandy Loam	same	
29.5	Walton	FL	no survey				

Notes:

1.SCS is the abbreviation for Soil Conservation Service.

2. When a soil type is listed under soil type used, it indicates that the original survey did not have quantitative information for the soil shown as most abundant. In this case, a similar soil from a nearby county was used.

3. If more than one soil is listed, an average was taken of the ones listed.

Appendix A: Table 6

Soil Data: Detail of Soil Properties

Cecil Sandy Loam — Spartanburg, SC

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 5	clay loam	0.63 – 2.0	0.10
5 – 43	clay	0.63 – 2.0	0.13
43 – 72	clay loam	0.63 – 2.0	0.12

Cecil Sandy Loam — Greenwood, SC

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 5	sandy loam	2.0 – 6.0	0.12 – 0.14
5 – 44	clay	0.6 – 2.0	0.13 – 0.15
44 – 77	clay loam, loam	0.6 – 2.0	0.13 – 0.15

Troup Fine Sand — Richmond, GA

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 54	fine sand	6.0 – 20.0	0.05 – 0.10
54 – 80	sandy clay loam, sandy loam	0.6 – 2.0	0.10 – 0.13

Dothan Loamy Sand — Burke, GA

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 12	loamy sand	2.0 – 6.0	0.06 – 0.10
12 – 48	sandy clay loam, sandy loam	0.6 – 2.0	0.12 – 0.16
48 – 62	sandy clay loam, sandy clay	0.2 – 0.6	0.08 – 0.12

Osier Soils — Candler, GA

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 6	loamy fine sand	6.0 – 20.0	0.10 – 0.15
6 – 62	sand, loamy sand, loamy fine sand	6.0 – 20.0	0.03 – 0.10

Appendix A: Table 6
(continued)

Pelham Loamy Sand — Tattnall, GA

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 32	loamy sand	6.0 – 20.0	0.05 – 0.08
32 – 72	sandy clay loam, sandy loam	0.6 – 2.0	0.10 – 0.13

Tifton Loamy Sand — Tattnall, GA

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 9	loamy sand	6.0 – 20.0	0.03 – 0.08
9 – 12	sandy loam, sandy clay loam	6.0 – 20.0	0.08 – 0.12
12 – 36	sandy clay loam	0.6 – 2.0	0.12 – 0.15
36 – 62	sandy clay loam	0.6 – 2.0	0.10 – 0.13

Plummer Soils — Wayne, GA

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 40	sand	5.0 – 10.0	0.10
40 – 50	sandy loam, sandy clay loam	0.8 – 2.5	0.10

Rutledge Sand — Wayne, GA

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 12	sand	2.5 – 5.0	0.10
12 – 40	sand	5.0 – 10.0	0.10
40 – 50	loamy sand	2.5 – 5.0	0.10

Candler Sand — Marion, FL

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 67	sand	>20	0.02 – 0.05
67 – 99	sand, fine sand	6.0 – 20.0	0.05 – 0.08

Appendix A: Table 6
(continued)

Pomona Fine Sand — Hardee, FL

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 3	fine sand	6.0 – 20.0	0.05 – 0.10
3 – 27	sand, fine sand	6.0 – 20.0	0.03 – 0.08
27 – 46	sand, fine sand	0.6 – 2.0	0.10 – 0.15
46 – 57	sand, fine sand	6.0 – 20.0	0.03 – 0.08
57 – 80	sandy clay loam, sandy loam,sandy clay	0.2 – 0.6	0.13 – 0.17

Immokalee Fine Sand — Lee, FL

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 9	sand	6.0 – 20.0	0.05 – 0.10
9 – 36	fine sand, sand	6.0 – 20.0	0.02 – 0.05
36 – 55	fine sand, sand	0.6 – 2.0	0.10 – 0.25
55 – 80	fine sand, sand	6.0 – 20.0	0.02 – 0.05

Baxter Cherty Silt Loam — Barren, KY

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 8	cherty silt loam	0.63 – 2.0	0.15
8 – 22	cherty silty clay loam	0.63 – 2.0	0.12
22 – 52	cherty silty clay	0.2 – 2.0	0.11
52 – 72	chert beds	–	–

Bodine Cherty Silt Loam — DeKalb, TN

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 43	cherty silt loam	6.3 – 20.0	0.10
43 – 79	cherty silty clay loam	6.3 – 20.0	0.10

Mountview Silt Loam — DeKalb, TN

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 11	silt loam	0.63 – 2.0	0.20
11 – 30	silty clay loam	0.63 – 2.0	0.17
30 – 60	clay	0.63 – 2.0	0.12

Appendix A: Table 6
(continued)

Hartsells Fine Sandy Loam — Etowah, AL

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 11	fine sandy loam	2.0 – 6.0	0.12 – 0.18
11 – 31	fine sandy loam, sandy clay loam, loam	0.6 – 2.0	0.13 – 0.18

Hartsells Fine Sandy Loam — Chatoogah, GA

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 7	fine sandy loam	2.0 – 6.0	0.12 – 0.18
7 – 40	clay loam, sandy clay loam	0.6 – 2.0	0.13 – 0.18

Hartsells Fine Sandy Loam — Blount, AL

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 6	fine sandy loam	2.0 – 6.0	0.12 – 0.18
6 – 38	loam	0.6 – 2.0	0.13 – 0.18

Louisa Slaty Loam — Randolph, AL

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 9	gravelly sandy loam	2.0 – 6.3	0.08 – 0.12
9 – 24	loam, sandy loam	2.0 – 6.3	0.10 – 0.15

Cecil Gravelly Sandy Loam — Randolph, AL

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 6	gravelly sandy loam, gravelly clay loam	2.0 – 6.3	0.08 – 0.14
6 – 62	clay	0.63 – 2.0	0.08 – 0.16

Luverne — Coffee, AL

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 5	fine sandy loam	2.0 – 6.0	0.06 – 0.15
5 – 36	clay loam, sandy clay, clay	0.2 – 0.6	0.12 – 0.18
36 – 65	clay loam, sandy clay loam	0.2 – 0.6	0.12 – 0.18

Appendix A: Table 6
(continued)

Dothan Sandy Loam — Geneva, AL

Horizon (inches)	Description of Layer	Permeability (inches/hour)	Available Water Capacity (in/in)
0 – 6	sandy loam	2.0 – 6.0	0.10 – 0.14
6 – 26	sandy clay loam	0.6 – 2.0	0.12 – 0.16
26 – 65	sandy clay loam	0.2 – 0.6	0.12 – 0.16

Appendix A: Table 7

Canadian Climatic Data

Toronto, Ontario

Daily Temperature Maximums (° C)

day of month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1	–0.5	–1.6	1.5	7.7	15.0	21.4	25.8	26.4	24.4	17.9	11.1	4.3
2	–0.6	–1.6	1.7	8.0	15.2	21.7	25.9	26.3	24.2	17.7	10.8	3.9
3	–0.7	–1.7	1.9	8.3	15.4	21.9	26.0	26.3	24.1	17.4	10.6	3.6
4	–0.8	–1.7	2.0	8.6	15.6	22.1	26.1	26.2	24.0	17.2	10.3	3.3
5	–0.9	–1.7	2.1	8.9	15.8	22.3	26.3	26.2	23.8	17.0	10.1	3.1
6	–1.1	–1.7	2.2	9.2	16.0	22.5	26.4	26.1	23.7	16.8	9.9	2.8
7	–1.1	–1.6	2.4	9.5	16.2	22.7	26.5	26.1	23.4	16.6	9.6	2.6
8	–1.2	–1.5	2.5	9.8	16.5	22.8	26.6	26.0	23.2	16.5	9.4	2.4
9	–1.2	–1.4	2.7	10.1	16.7	22.9	26.6	25.9	22.9	16.3	9.3	2.2
10	–1.2	–1.3	2.8	10.5	17.0	23.1	26.7	25.9	22.6	16.1	9.1	2.1
11	–1.2	–1.1	3.0	10.8	17.2	23.2	26.8	25.8	22.4	15.9	8.9	1.9
12	–1.3	–1.0	3.2	11.1	17.5	23.3	26.9	25.8	22.1	15.7	8.7	1.7
13	–1.3	–0.9	3.3	11.4	17.7	23.4	26.9	25.7	21.8	15.5	8.5	1.6
14	–1.3	–0.7	3.5	11.7	18.0	23.6	27.0	25.7	21.6	15.3	8.3	1.4
15	–1.3	–0.6	3.7	12.0	18.2	23.7	27.0	25.6	21.3	15.1	8.1	1.2
16	–1.3	–0.4	3.9	12.2	18.4	23.8	27.1	25.6	21.1	14.8	7.8	1.0
17	–1.3	–0.3	4.1	12.5	18.6	24.0	27.1	25.5	20.9	14.6	7.6	0.9
18	–1.3	–0.1	4.3	12.7	18.8	24.1	27.1	25.5	20.6	14.4	7.4	0.8
19	–1.3	0.0	4.5	12.9	19.0	24.2	27.1	25.5	20.4	14.2	7.2	0.7
20	–1.4	0.2	4.7	13.1	19.2	24.3	27.1	25.4	20.2	13.9	6.9	0.6
21	–1.4	0.4	4.9	13.2	19.3	24.4	27.1	25.4	19.9	13.7	6.6	0.6
22	–1.4	0.5	5.1	13.3	19.4	24.6	27.0	25.4	19.7	13.4	6.3	0.5
23	–1.4	0.7	5.3	13.5	19.6	24.7	27.0	25.3	19.5	13.2	6.1	0.4
24	–1.5	0.8	5.6	13.7	19.8	24.8	26.9	25.3	19.3	12.9	5.8	0.3
25	–1.5	0.9	5.8	13.8	20.0	25.0	26.9	25.2	19.1	12.7	5.6	0.2
26	–1.6	1.0	6.0	14.0	20.1	25.1	26.8	25.2	18.8	12.4	5.3	0.2
27	–1.6	1.2	6.3	14.2	20.3	25.2	26.7	25.0	18.6	12.2	5.0	0.1
28	–1.6	1.3	6.6	14.4	20.6	25.3	26.7	24.9	18.4	11.9	4.8	–0.1
29	–1.6		6.9	14.6	20.8	25.4	26.6	24.8	18.2	11.7	4.5	–0.2
30	–1.6		7.1	14.8	21.0	25.5	26.6	24.6	18.0	11.5	4.3	–0.3
31	–1.6		7.4		21.2		26.5	24.5		11.3		–0.4

Appendix A: Table 7
(continued)

Toronto, Ontario

Daily Temperature Minimums (°C)

day of month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1	–6.8	–8.4	–4.9	0.3	6.2	12.0	16.1	17.4	15.4	9.7	4.6	–1.6
2	–6.9	–8.4	–4.7	0.5	6.4	12.2	16.2	17.3	15.3	9.5	4.5	–1.9
3	–7.1	–8.5	–4.6	0.7	6.5	12.4	16.3	17.3	15.1	9.3	4.3	–2.2
4	–7.2	–8.5	–4.4	0.9	6.7	12.6	16.4	17.3	15.0	9.2	4.1	–2.4
5	–7.4	–8.5	–4.3	1.1	6.8	12.8	16.5	17.2	14.8	9.0	4.0	–2.7
6	–7.5	–8.6	–4.1	1.3	6.9	13.0	16.6	17.2	14.7	8.8	3.8	–2.9
7	–7.6	–8.5	–4.0	1.5	7.1	13.2	16.7	17.1	14.5	8.6	3.6	–3.2
8	–7.7	–8.4	–3.9	1.8	7.4	13.3	16.8	17.0	14.3	8.5	3.5	–3.4
9	–7.8	–8.3	–3.7	2.0	7.6	13.5	16.9	17.0	14.0	8.3	3.3	–3.6
10	–7.9	–8.1	–3.6	2.3	7.8	13.7	17.0	16.9	13.8	8.2	3.1	–3.8
11	–7.9	–8.0	–3.5	2.6	8.0	13.9	17.1	16.8	13.6	8.0	3.0	–4.0
12	–8.0	–7.8	–3.3	2.8	8.2	14.0	17.2	16.7	13.4	7.8	2.8	–4.2
13	–8.0	–7.7	–3.2	3.1	8.4	14.1	17.3	16.7	13.2	7.7	2.6	–4.4
14	–8.1	–7.5	–3.0	3.4	8.5	14.3	17.4	16.6	13.0	7.5	2.5	–4.6
15	–8.1	–7.4	–2.9	3.6	8.7	14.4	17.4	16.6	12.8	7.3	2.3	–4.8
16	–8.1	–7.2	–2.7	3.8	8.9	14.5	17.5	16.5	12.6	7.2	2.1	–5.0
17	–8.1	–7.0	–2.6	4.0	9.1	14.7	17.6	16.5	12.4	7.0	1.9	–5.1
18	–8.1	–6.8	–2.4	4.2	9.3	14.8	17.6	16.5	12.2	6.8	1.7	–5.3
19	–8.1	–6.7	–2.2	4.4	9.5	14.9	17.7	16.4	12.0	6.7	1.5	–5.4
20	–8.1	–6.5	–2.0	4.5	9.7	15.0	17.7	16.4	11.8	6.5	1.3	–5.5
21	–8.1	–6.3	–1.9	4.7	9.8	15.1	17.7	16.4	11.6	6.4	1.0	–5.6
22	–8.1	–6.1	–1.7	4.9	10.0	15.2	17.7	16.4	11.4	6.2	0.8	–5.7
23	–8.1	–5.9	–1.5	5.0	10.2	15.3	17.6	16.3	11.2	6.1	0.6	–5.8
24	–8.1	–5.8	–1.4	5.1	10.4	15.4	17.6	16.3	11.0	5.9	0.3	–5.8
25	–8.2	–5.6	–1.2	5.2	10.5	15.5	17.6	16.3	10.8	5.8	0.1	–5.9
26	–8.2	–5.5	–1.0	5.4	10.7	15.6	17.6	16.2	10.6	5.6	–0.2	–5.9
27	–8.2	–5.3	–0.8	5.5	10.9	15.7	17.5	16.1	10.4	5.4	–0.5	–6.1
28	–8.3	–5.2	–0.6	5.7	11.1	15.8	17.5	15.9	10.2	5.3	–0.7	–6.2
29	–8.3		–0.4	5.8	11.3	15.9	17.4	15.8	10.0	5.1	–1.0	–6.4
30	–8.4		–0.2	6.0	11.5	16.0	17.4	15.7	9.9	4.9	–1.3	–6.5
31	–8.4		0.0		11.7		17.4	15.5		4.8		–6.7

Appendix A: Table 7
(continued)

Sherbrooke Airport, Quebec

Daily Temperature Maximums (°C)

day of month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1	–5.0	–5.2	–1.1	5.2	13.9	20.7	23.9	24.4	21.5	15.7	8.9	0.5
2	–5.1	–5.2	–0.9	5.5	14.1	20.9	24.0	24.4	21.4	15.4	8.7	0.2
3	–5.2	–5.2	–0.8	5.8	14.3	21.1	24.1	24.3	21.3	15.2	8.4	–0.1
4	–5.3	–5.3	–0.6	6.0	14.5	21.2	24.2	24.3	21.1	15.0	8.2	–0.5
5	–5.4	–5.4	–0.4	6.2	14.8	21.4	24.2	24.3	20.9	14.8	7.9	–0.9
6	–5.5	–5.4	–0.2	6.4	15.1	21.6	24.3	24.2	20.7	14.6	7.6	–1.2
7	–5.6	–5.3	0.0	6.7	15.4	21.7	24.4	24.1	20.6	14.3	7.2	–1.5
8	–5.7	–5.2	0.2	7.1	15.7	21.8	24.4	24.0	20.4	14.1	6.9	–1.7
9	–5.7	–5.1	0.4	7.5	16.0	21.9	24.5	23.9	20.2	13.9	6.5	–2.0
10	–5.7	–4.9	0.6	7.9	16.3	22.0	24.6	23.7	20.0	13.7	6.2	–2.2
11	–5.6	–4.7	0.7	8.3	16.6	22.1	24.7	23.6	19.8	13.6	5.9	–2.5
12	–5.6	–4.6	0.9	8.7	16.8	22.2	24.7	23.6	19.6	13.4	5.5	–2.7
13	–5.5	–4.4	1.1	9.0	17.1	22.3	24.8	23.5	19.4	13.2	5.2	–2.9
14	–5.5	–4.3	1.3	9.3	17.3	22.4	24.9	23.4	19.3	13.0	4.9	–3.2
15	–5.4	–4.1	1.5	9.7	17.6	22.5	24.9	23.3	19.1	12.8	4.7	–3.4
16	–5.2	–3.9	1.7	10.0	17.8	22.7	25.0	23.2	18.8	12.6	4.4	–3.5
17	–5.1	–3.7	2.0	10.4	18.0	22.8	25.0	23.1	18.6	12.4	4.2	–3.7
18	–5.0	–3.4	2.2	10.7	18.3	22.9	25.0	23.1	18.5	12.2	3.9	–3.8
19	–4.9	–3.2	2.4	11.0	18.5	23.0	24.9	23.0	18.3	12.0	3.7	–3.9
20	–4.8	–3.0	2.7	11.2	18.7	23.0	24.9	22.9	18.1	11.8	3.5	–4.0
21	–4.7	–2.7	2.9	11.4	18.8	23.1	24.9	22.8	17.9	11.6	3.3	–4.1
22	–4.7	–2.5	3.1	11.6	19.0	23.2	24.9	22.8	17.7	11.4	3.1	–4.1
23	–4.7	–2.2	3.3	11.9	19.1	23.3	24.9	22.7	17.5	11.2	2.8	–4.2
24	–4.7	–1.9	3.5	12.1	19.3	23.4	24.8	22.6	17.3	11.0	2.6	–4.3
25	–4.7	–1.7	3.6	12.3	19.5	23.5	24.7	22.5	17.0	10.7	2.4	–4.4
26	–4.8	–1.5	3.8	12.6	19.6	23.6	24.7	22.4	16.8	10.5	2.1	–4.5
27	–4.9	–1.3	4.0	12.9	19.8	23.6	24.6	22.2	16.6	10.2	1.8	–4.6
28	–5.0	–1.1	4.2	13.2	20.0	23.7	24.5	22.0	16.4	9.9	1.5	–4.7
29	–5.1		4.4	13.5	20.1	23.8	24.5	21.9	16.2	9.6	1.2	–4.8
30	–5.2		4.6	13.8	20.3	23.8	24.4	21.7	16.0	9.3	0.9	–4.9
31	–5.3		4.8		20.5		24.4	21.5		9.0		–5.0

Appendix A: Table 7
(continued)

Sherbrooke Airport, Quebec

Daily Temperature Minimums (°C)

day of month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1	–17.4	–18.5	–14.4	–6.4	0.6	6.2	10.0	11.2	7.8	2.5	–1.5	–9.2
2	–17.6	–18.6	–14.1	–6.1	0.8	6.3	10.1	11.2	7.7	2.3	–1.6	–9.5
3	–17.8	–18.8	–13.8	–5.8	0.9	6.4	10.2	11.1	7.5	2.1	–1.6	–9.9
4	–18.0	–19.0	–13.5	–5.5	1.1	6.6	10.3	11.1	7.3	2.0	–1.7	–10.3
5	–18.4	–19.3	–13.1	–5.2	1.3	6.7	10.3	11.1	7.1	1.8	–1.7	–10.7
6	–18.5	–19.5	–12.8	–4.9	1.5	6.9	10.4	11.1	6.9	1.7	–1.8	–11.1
7	–18.6	–19.5	12.6	–4.5	1.7	7.1	10.5	10.9	6.7	1.5	–1.9	–11.4
8	–18.7	–19.5	–12.4	–4.1	2.0	7.2	10.6	10.8	6.4	1.4	–2.1	–11.8
9	–18.7	–19.4	–12.1	–3.8	2.2	7.4	10.7	10.6	6.2	1.3	–2.3	–12.1
10	–18.7	–19.3	–11.9	–3.5	2.4	7.6	10.8	10.5	6.0	1.2	–2.5	–12.4
11	–18.7	–19.2	–11.7	–3.2	2.6	7.7	10.9	10.4	5.8	1.1	–2.8	–12.6
12	–18.7	–19.0	–11.5	–2.9	2.9	7.9	11.0	10.2	5.6	1.0	–3.0	–12.9
13	–18.6	–18.9	–11.2	–2.6	3.2	8.1	11.0	10.1	5.5	0.8	–3.3	–13.2
14	–18.5	–18.7	–11.0	–2.4	3.4	8.3	11.2	10.0	5.3	0.7	–3.6	–13.4
15	–18.4	–18.4	–10.7	–2.2	3.6	8.5	11.2	9.9	5.1	0.6	–3.9	–13.7
16	–18.2	–18.2	–10.5	–1.9	3.8	8.6	11.3	9.7	5.0	0.4	–4.3	–13.9
17	–18.0	–17.9	–10.2	–1.7	4.0	8.8	11.3	9.6	4.8	0.3	–4.6	–14.1
18	–17.8	–17.6	–9.9	–1.4	4.1	8.9	11.3	9.5	4.7	0.1	–4.9	–14.3
19	–17.7	–17.3	–9.6	–1.2	4.3	9.1	11.3	9.4	4.5	0.0	–5.2	–14.5
20	–17.5	–17.0	–9.3	–1.0	4.4	9.2	11.4	9.3	4.4	–0.2	–5.5	–14.6
21	–17.3	–16.7	–9.0	–0.7	4.5	9.3	11.4	9.3	4.3	–0.3	–5.8	–14.8
22	–17.2	–16.4	–8.7	–0.6	4.7	9.4	11.4	9.2	4.1	–0.4	–6.1	–14.9
23	–17.2	–16.1	–8.5	–0.5	4.8	9.4	11.4	9.1	4.0	–0.5	–6.2	–15.1
24	–17.2	–15.8	–8.3	–0.4	4.9	9.5	11.4	9.1	3.9	–7.0	–6.6	–15.2
25	–17.2	–15.4	–8.0	–0.3	5.0	9.5	11.4	9.0	3.7	–0.9	–6.9	–15.4
26	–17.3	–15.1	–7.8	–0.2	5.2	9.6	11.4	8.9	3.6	–1.0	–7.3	–15.6
27	–17.5	–14.8	–7.6	0.0	5.4	9.6	11.4	8.7	3.4	–1.1	–7.7	–15.8
28	–17.8	–14.6	–7.4	0.2	5.5	9.7	11.3	8.5	3.2	–1.2	–8.1	–16.1
29	–18.0		–7.1	0.3	5.7	9.7	11.3	8.3	3.0	–1.3	–8.5	–16.5
30	–18.3		–6.9	0.5	5.9	9.8	11.3	8.1	2.8	–1.4	–8.9	–16.8
31	–18.4		–6.7		6.1		11.2	7.9		–1.5		–17.1

Appendix A: Table 7
(continued)

Quebec Airport, Quebec

day of month	Daily Temperature Maximums (° C) Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1	–7.2	–7.5	–3.1	3.5	12.8	20.1	24.1	24.5	21.1	14.5	7.2	–1.5
2	–7.3	–7.5	–2.8	3.7	13.2	20.3	24.2	24.4	20.9	14.2	6.9	–1.8
3	–7.5	–7.5	–2.6	3.9	13.5	20.4	24.3	24.3	20.7	14.0	6.6	–2.1
4	–7.6	–7.5	–2.4	4.2	13.8	20.6	24.4	24.2	20.5	13.8	6.4	–2.4
5	–7.7	–7.6	–2.2	4.4	14.1	20.8	24.5	24.2	20.3	13.6	6.1	–2.7
6	–7.8	–7.6	–2.0	4.7	14.5	21.0	24.6	24.1	20.1	13.3	5.8	–3.1
7	–7.8	–7.5	–1.8	5.0	14.8	21.2	24.7	24.0	19.9	13.1	5.5	–3.4
8	–7.8	–7.3	–1.6	5.3	15.1	21.4	24.8	23.9	19.6	12.9	5.3	–3.7
9	–7.8	–7.2	–1.4	5.7	15.3	21.5	24.8	23.8	19.4	12.7	5.0	–3.9
10	–7.8	–7.1	–1.2	6.0	15.6	21.7	24.9	23.7	19.1	12.5	4.7	–4.2
11	–7.8	–6.9	–1.0	6.4	15.9	21.8	25.0	23.6	18.9	12.3	4.4	–4.4
12	–7.7	6.7	–0.8	6.7	16.1	22.0	25.1	23.5	18.7	12.1	4.2	–4.7
13	–7.7	–6.5	–0.6	7.1	16.4	22.2	25.1	23.5	18.4	11.9	3.9	–4.9
14	–7.6	–6.4	–0.4	7.4	16.6	22.3	25.2	23.4	18.2	11.7	3.6	–5.1
15	–7.6	–6.2	–0.2	7.8	16.9	22.4	25.3	23.3	18.0	11.5	3.3	–5.3
16	–7.5	–6.0	0.0	8.1	17.1	22.6	25.3	23.2	17.8	11.3	3.1	–5.5
17	–7.5	–5.8	0.2	8.5	17.3	22.7	25.3	23.1	17.6	11.0	2.8	–5.7
18	–7.4	–5.6	0.4	8.8	17.5	22.8	25.4	23.0	17.4	10.7	2.5	–5.8
19	–7.4	–5.4	0.6	9.1	17.7	22.9	25.3	22.9	17.2	10.5	2.2	–6.0
20	–7.3	–5.2	0.9	9.4	17.9	23.0	25.3	22.8	17.0	10.3	2.0	–6.1
21	–7.3	–5.0	1.1	9.7	18.1	23.1	25.3	22.7	16.7	10.1	1.7	–6.2
22	–7.3	–4.7	1.3	10.0	18.3	23.2	25.2	22.6	16.5	9.8	1.4	–6.2
23	–7.2	–4.4	1.5	10.3	18.4	23.3	25.2	22.5	16.3	9.6	1.2	–6.3
24	–7.2	–4.2	1.7	10.6	18.6	23.4	25.1	22.4	16.0	9.3	0.9	–6.4
25	–7.3	–4.0	1.9	10.9	18.8	23.5	25.0	22.3	15.7	9.0	0.6	–6.5
26	–7.3	–3.8	2.1	11.2	18.9	23.6	25.0	22.2	15.5	8.7	0.3	–6.6
27	–7.4	–3.6	2.3	11.5	19.1	23.7	24.9	22.0	15.3	8.5	0.0	–6.7
28	–7.4	–3.4	2.6	11.8	19.3	23.8	24.8	21.8	15.0	8.2	–0.4	–6.8
29	–7.4		2.8	12.1	19.5	23.9	24.7	21.6	14.8	7.9	–0.7	–6.9
30	–7.4		3.0	12.4	19.7	24.0	24.6	21.4	14.6	7.7	–1.1	–7.0
31	–7.4		3.3		19.9		24.5	21.3		7.4		–7.1

Appendix A: Table 7
(continued)

Quebec Airport, Quebec

Daily Temperature Minimums (° C)

day of month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1	–15.9	–17.0	–12.5	–5.0	1.7	7.9	12.3	13.1	10.0	4.6	–0.3	–8.6
2	–16.0	–17.0	–12.3	–4.7	1.9	8.0	12.3	13.0	9.8	4.4	–0.5	–9.0
3	–16.2	–17.1	–12.1	–4.5	2.1	8.2	12.4	13.0	9.6	4.2	–0.6	–9.4
4	–16.3	–17.2	–11.9	–4.2	2.3	8.4	12.5	12.9	9.5	4.1	–0.8	–9.8
5	–16.4	–17.3	–11.7	–4.0	2.4	8.6	12.6	12.9	9.3	3.9	–0.9	–10.2
6	–16.6	–17.3	–11.5	–3.7	2.6	8.8	12.7	12.8	9.1	3.8	–1.0	–10.6
7	–16.7	–17.3	–11.3	–3.4	2.9	9.0	12.8	12.8	8.9	3.6	–1.3	–10.9
8	–16.8	–17.2	–11.1	–3.2	3.1	9.2	12.9	12.7	8.6	3.4	–1.5	–11.3
9	–16.8	–17.0	–10.9	–2.9	3.4	9.4	13.0	12.6	8.4	3.3	–1.7	–11.7
10	–16.8	–16.9	–10.7	–2.6	3.6	9.6	13.0	12.5	8.1	3.1	–1.9	–12.1
11	–16.8	–16.7	–10.5	–2.3	3.8	9.8	13.1	12.4	7.9	3.0	–2.1	–12.4
12	–16.8	–16.5	–10.2	–2.1	4.0	10.0	13.2	12.3	7.7	2.8	–2.4	–12.7
13	–16.8	–16.3	–10.0	–1.9	4.3	10.2	13.3	12.2	7.5	2.6	–2.6	–13.0
14	–16.8	–16.1	–9.8	–1.7	4.5	10.4	13.4	12.1	7.3	2.5	–2.9	–13.3
15	–16.7	–15.9	–9.5	–1.4	4.7	10.5	13.5	12.0	7.1	2.3	–3.2	–13.5
16	–16.7	–15.6	–9.3	–1.2	5.0	10.7	13.5	11.9	6.9	2.1	–3.4	–13.8
17	–16.6	–15.4	–9.0	–1.0	5.2	10.9	13.6	11.9	6.8	1.9	–3.7	–14.0
18	–16.6	–15.1	–8.7	–0.8	5.4	11.0	13.6	11.4	6.6	1.8	–4.0	–14.2
19	–16.6	–14.9	–8.4	–0.5	5.6	11.2	13.6	11.7	6.4	1.6	–4.3	–14.3
20	–16.5	–14.6	–8.2	–0.3	5.8	11.3	13.6	11.6	6.2	1.4	–4.6	–14.5
21	–16.5	–14.4	–7.9	–0.1	5.9	11.4	13.6	11.5	6.1	1.3	–4.9	–14.6
22	–16.5	–14.1	–7.6	0.0	6.1	11.5	13.5	11.4	5.9	1.1	–5.2	–14.7
23	–16.4	–13.9	–7.3	0.2	6.3	11.6	13.5	11.4	5.8	0.9	–5.5	–14.8
24	–16.4	–13.6	–7.1	0.4	6.4	11.7	13.5	11.3	5.6	0.8	–5.8	–14.9
25	–16.5	–13.4	–6.9	0.5	6.6	11.8	13.5	11.2	5.5	0.6	–6.1	–15.0
26	–16.5	–13.2	–6.6	0.7	6.7	11.9	13.4	11.1	5.4	0.4	–6.5	–15.1
27	–16.6	–13.0	–6.4	0.9	6.9	11.9	13.3	10.9	5.2	0.3	–6.9	–15.2
28	–16.7	–12.8	–6.1	1.1	7.1	12.0	13.3	10.7	5.0	0.2	–7.3	–15.4
29	–16.8		–5.8	1.3	7.3	12.1	13.2	10.5	4.9	0.0	–7.7	–15.5
30	–16.8		–5.6	1.5	7.5	12.2	13.2	10.4	4.7	–0.1	–8.1	–15.7
31	–16.9		–5.3		7.7		13.1	10.2		–0.3		–15.8

Appendix A: Table 7
(continued)

Sudbury Airport, Ontario

Daily Temperature Maximums (° C)

day of month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1	–8.3	–8.8	–4.0	2.6	12.3	19.7	23.6	23.9	20.6	13.8	6.4	–2.0
2	–8.5	–8.9	–3.8	2.9	12.6	19.9	23.7	23.9	20.4	13.6	6.1	–3.0
3	–8.6	–8.9	–3.6	3.2	12.9	20.1	23.8	23.8	20.2	13.4	5.8	–3.3
4	–8.8	–9.0	–3.3	3.5	13.1	20.2	24.0	23.7	20.0	13.3	5.5	–3.6
5	–8.9	–9.0	–3.1	3.8	13.4	20.4	24.1	23.7	19.8	13.1	5.2	–4.0
6	–9.0	–8.9	–2.9	4.1	13.6	20.6	24.2	23.6	19.6	12.9	4.9	–4.3
7	–9.0	–8.8	–2.6	4.6	13.9	20.7	24.3	23.5	19.3	12.7	4.6	–4.5
8	–9.1	–8.7	–2.4	5.0	14.2	20.8	24.3	23.4	19.0	12.5	4.3	–4.7
9	–9.1	–8.6	–2.2	5.4	14.6	20.9	24.4	23.3	18.7	12.3	4.0	–4.9
10	–9.1	–8.5	–2.0	5.9	14.9	21.0	24.4	23.2	18.5	12.1	3.7	–5.1
11	–9.1	–8.3	–1.8	6.3	15.2	21.2	24.5	23.1	18.2	11.9	3.5	–5.3
12	–9.1	–8.1	–1.6	6.8	15.5	21.3	24.5	23.0	17.9	11.7	3.2	–5.5
13	–9.0	–7.9	–1.5	7.2	15.8	21.4	24.6	22.9	17.6	11.4	2.9	–5.7
14	–9.0	–7.7	–1.3	7.6	16.1	21.5	24.6	22.9	17.4	11.2	2.6	–5.9
15	–9.0	–7.5	–1.1	8.0	16.4	21.6	24.6	22.8	17.1	11.0	2.3	–6.1
16	–8.9	–7.2	–0.9	8.4	16.7	21.8	24.6	22.7	16.8	10.7	2.0	–6.2
17	–8.8	–7.0	–0.7	8.8	16.9	21.9	24.6	22.6	16.5	10.5	1.7	–6.4
18	–8.7	–6.8	–0.5	9.1	17.2	22.0	24.6	22.5	16.3	10.3	1.4	–6.5
19	–8.7	–6.6	–0.3	9.4	17.4	22.1	24.6	22.4	16.0	10.1	1.1	–6.6
20	–8.6	–6.4	–0.1	9.6	17.6	22.2	24.6	22.3	15.8	9.8	0.8	–6.7
21	–8.6	–6.1	0.0	9.8	17.8	22.4	24.5	22.2	15.6	9.6	0.5	–6.8
22	–8.6	–5.9	0.2	10.0	18.0	22.5	24.5	22.1	15.4	9.3	0.2	–6.9
23	–8.6	–5.7	0.4	10.3	18.2	22.7	24.4	22.0	15.2	9.0	–0.1	–7.0
24	–8.6	–5.4	0.6	10.5	18.3	22.8	24.4	21.9	15.0	8.8	–0.4	–7.1
25	–8.6	–5.2	0.8	10.7	18.5	23.0	24.3	21.8	14.8	8.5	–0.8	–7.3
26	–8.6	–5.0	1.0	10.9	18.6	23.1	24.2	21.7	14.6	8.2	–1.1	–7.4
27	–8.6	–4.7	1.3	11.2	18.8	23.2	24.2	21.5	14.4	7.9	–1.4	–7.5
28	–8.6	–4.4	1.6	11.5	19.0	23.3	24.1	21.3	14.3	7.6	–1.7	–7.7
29	–8.6		1.8	11.7	19.1	23.4	24.0	21.1	14.1	7.3	–2.0	–7.8
30	–8.6		2.1	12.0	19.3	23.5	24.0	20.9	13.9	7.0	–2.3	–8.0
31	–8.7		2.4		19.5		23.9	20.7		6.8		–8.1

Appendix A: Table 7
(continued)

Sudbury Airport, Ontario

Daily Temperature Minimums (°C)

day of month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1	–17.7	–19.2	–14.7	–6.9	1.4	8.0	12.3	13.0	10.2	4.4	–0.7	–10.1
2	–17.9	–19.3	–14.4	–6.6	1.6	8.2	12.4	13.0	10.0	4.3	–0.9	–10.5
3	–18.0	–19.3	–14.2	–6.3	1.8	8.3	12.5	12.9	9.8	4.2	–1.1	–10.9
4	–18.2	–19.4	–14.0	–6.0	2.0	8.5	12.6	12.9	9.6	4.0	–1.3	–11.3
5	–18.4	–19.5	–13.8	–5.7	2.2	8.7	12.7	12.8	9.4	3.9	–1.4	–11.7
6	–18.6	–19.5	–13.6	–5.3	2.4	8.9	12.8	12.8	9.2	3.7	–1.6	–12.1
7	–18.7	–19.4	–13.4	–4.9	2.6	9.0	12.8	12.7	9.0	3.6	–1.9	–12.4
8	–18.7	–19.3	–13.2	–4.5	2.9	9.2	12.9	12.6	8.7	3.5	–2.1	–12.8
9	–18.7	–19.2	–13.0	–4.1	3.1	9.3	13.0	12.5	8.5	3.3	–2.4	–13.1
10	–18.7	–19.0	–12.8	–3.7	3.4	9.4	13.0	12.4	8.2	3.2	–2.6	–13.4
11	–18.7	–18.8	–12.5	–3.4	3.7	9.6	13.1	12.3	8.0	3.0	–2.9	–13.7
12	–18.7	–18.6	–12.3	–3.0	3.9	9.7	13.2	12.3	7.8	2.8	–3.2	–14.0
13	–18.7	–18.4	–12.1	–2.6	4.2	9.8	13.2	12.2	7.6	2.7	–3.5	–14.2
14	–18.7	–18.2	–11.9	–2.3	4.4	10.0	13.3	12.1	7.4	2.5	–3.8	–14.5
15	–18.6	–18.0	–11.6	–2.0	4.6	10.2	13.4	12.1	7.2	2.3	–4.1	–14.7
16	–18.6	–17.8	–11.4	–1.7	4.8	10.3	13.4	12.0	7.0	2.1	–4.4	–15.0
17	–18.5	–17.6	–11.1	–1.4	5.0	10.4	13.4	12.0	6.8	2.0	–4.7	–15.2
18	–18.4	–17.3	–10.8	–1.1	5.3	10.6	13.4	11.9	6.6	1.8	–5.1	–15.4
19	–18.4	–17.1	–10.6	–0.8	5.5	10.7	13.4	11.8	6.4	1.7	–5.4	–15.6
20	–18.3	–16.8	–10.3	–0.6	5.7	10.9	13.4	11.8	6.2	1.5	–5.8	–15.7
21	–18.3	–16.6	–10.1	–0.4	5.9	11.0	13.4	11.7	6.8	1.3	–6.2	–15.9
22	–18.3	–16.4	–9.8	–0.2	6.1	11.2	13.4	11.7	5.8	1.1	–6.5	–16.0
23	–18.3	–16.1	–9.6	0.0	6.3	11.3	13.4	11.6	5.6	0.9	–6.9	–16.2
24	–18.4	–15.9	–9.3	0.1	6.5	11.5	13.3	11.6	5.4	0.7	–7.3	–16.3
25	–18.4	–15.7	–9.1	0.3	6.7	11.6	13.3	11.5	5.3	0.6	–7.7	–16.4
26	–18.5	–15.4	–8.8	0.4	6.8	11.7	13.3	11.4	5.1	0.4	–8.1	–16.6
27	–18.6	–15.3	–8.5	0.6	7.0	11.8	13.2	11.2	5.0	0.2	–8.5	–16.8
28	–18.6	–15.1	–8.1	0.8	7.2	11.9	13.1	11.0	4.8	0.0	–8.9	–17.0
29	–18.7		–7.8	1.0	7.4	12.0	13.1	10.8	4.7	–0.1	–9.3	–17.1
30	–18.8		–7.4	1.2	7.6	12.1	13.0	10.6	4.5	–0.3	–9.7	–17.3
31	–19.0		–7.1		7.7		13.0	10.4		–0.5		–17.5

Appendix A: Table 7
(continued)

Thunder Bay Airport, Ontario

Daily Temperature Maximums (° C)

day of month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1	–8.3	–8.6	–3.5	3.9	12.2	18.4	23.1	24.2	20.5	14.0	6.6	–2.8
2	–8.5	–8.5	–3.3	4.2	12.4	18.6	23.2	24.1	20.2	13.9	6.3	–3.1
3	–8.7	–8.3	–3.1	4.5	12.7	18.7	23.4	24.1	20.0	13.8	5.9	–3.4
4	–8.9	–8.2	–2.9	4.8	12.9	18.8	23.5	24.0	19.8	13.6	5.6	–3.7
5	–9.1	–8.0	–2.7	5.2	13.1	19.1	23.7	23.9	19.6	13.5	5.2	–3.9
6	–9.3	–7.9	–2.5	5.5	13.4	19.3	23.8	23.9	19.4	13.3	4.9	–4.2
7	–9.3	–7.7	–2.3	5.8	13.6	19.4	23.9	23.8	19.1	13.2	4.5	–4.5
8	–9.4	–7.5	–2.0	6.2	13.9	19.6	24.0	23.7	18.8	13.0	4.2	–4.8
9	–9.5	–7.2	–1.7	6.5	14.2	19.8	24.1	23.6	18.5	12.8	3.9	–5.0
10	–9.5	–7.0	–1.5	6.9	14.4	19.9	24.1	23.5	18.2	12.7	3.6	–5.2
11	–9.6	–6.9	–1.3	7.3	14.7	20.1	24.2	23.4	17.9	12.5	3.3	–5.4
12	–9.6	–6.7	–1.1	7.6	14.9	20.2	24.3	23.3	17.6	12.3	2.9	–5.5
13	–9.7	–6.5	–0.8	7.9	15.2	20.4	24.4	23.2	17.4	12.1	2.6	–5.7
14	–9.7	–6.3	–0.6	8.2	15.4	20.5	24.5	23.2	17.1	11.9	2.3	–5.8
15	–9.7	–6.1	–0.4	8.5	15.6	20.6	24.6	23.1	16.9	11.7	2.0	–5.9
16	–9.8	–5.9	–0.2	8.8	15.8	20.8	24.6	23.0	16.6	11.5	1.7	–6.1
17	–9.8	–5.7	0.0	9.0	16.0	20.9	24.7	22.9	16.4	11.2	1.4	–6.2
18	–9.8	–5.5	0.2	9.3	16.2	21.1	24.7	22.7	16.2	11.0	1.1	–6.3
19	–9.7	–5.3	0.4	9.6	16.3	21.2	24.8	22.6	15.9	10.7	0.8	–6.3
20	–9.7	–5.2	0.6	9.8	16.5	21.4	24.8	22.5	15.7	10.4	0.5	–6.4
21	–9.7	–5.0	0.8	10.0	16.6	21.6	24.8	22.4	15.5	10.2	0.2	–6.5
22	–9.7	–4.8	1.0	10.2	16.8	21.7	24.8	22.3	15.4	9.9	–0.1	–6.6
23	–9.7	–4.6	1.2	10.4	16.9	21.8	24.8	22.2	15.2	9.6	–0.4	–6.8
24	–9.7	–4.4	1.5	10.6	17.0	22.0	24.7	22.0	15.0	9.3	–0.7	–6.9
25	–9.7	–4.3	1.7	10.8	17.2	22.1	24.7	21.9	14.9	9.0	–1.0	–7.0
26	–9.6	–4.1	1.9	11.0	17.3	22.3	24.6	21.7	14.7	8.7	–1.3	–7.2
27	–9.4	–3.9	2.3	11.3	17.5	22.4	24.6	21.5	14.6	8.3	–1.6	–7.4
28	–9.3	–3.7	2.6	11.5	17.6	22.6	24.5	21.3	14.4	8.0	–1.9	–7.5
29	–9.1		2.9	11.7	17.8	22.7	24.5	21.1	14.3	7.7	–2.2	–7.7
30	–9.0		3.2	12.0	18.0	22.9	24.4	20.9	14.1	7.3	–2.5	–7.9
31	–8.8		3.5		18.2		24.3	20.7		7.0		–8.1

Appendix A: Table 7

(continued)

Thunder Bay Airport, Ontario

Daily Temperature Minimums (°C)

day of month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1	–19.7	–21.7	–16.5	–7.2	–0.6	5.1	9.7	10.8	8.1	2.4	–2.8	–12.6
2	–19.9	–21.6	–16.3	–6.9	–0.5	5.3	9.9	10.8	7.9	2.3	–3.0	–12.9
3	–20.1	–21.6	–16.0	–6.5	–0.4	5.5	10.0	10.8	7.7	2.2	–3.3	–13.3
4	–20.4	–21.6	–15.8	–6.2	–0.2	5.6	10.2	10.7	7.5	2.0	–3.5	–13.7
5	–20.6	–21.5	–15.5	–5.8	–0.1	5.8	10.3	10.6	7.3	1.9	–3.8	–14.0
6	–20.8	–21.5	–15.3	–5.4	0.0	6.0	10.5	10.6	7.2	1.8	–4.1	–14.4
7	–21.0	–21.3	–15.0	–5.1	0.2	6.1	10.6	10.5	6.9	1.7	–4.4	–14.7
8	–21.1	–21.1	–14.7	–4.8	0.4	6.2	10.7	10.4	6.7	1.6	–4.6	–14.9
9	–21.2	–20.9	–14.3	–4.5	0.6	6.3	10.8	10.4	6.4	1.4	–4.9	–15.1
10	–21.2	–20.7	–14.0	–4.2	0.8	6.5	10.9	10.3	6.2	1.3	–5.2	–15.3
11	–21.3	–20.6	–13.7	–3.9	1.1	6.6	11.0	10.2	5.9	1.2	–5.5	–15.5
12	–21.3	–20.4	–13.4	–3.6	1.3	6.7	11.0	10.2	5.7	1.0	–5.8	–15.7
13	–21.4	–20.2	–13.2	–3.3	1.5	6.9	11.1	10.1	5.5	0.9	–6.1	–15.9
14	–21.4	–20.1	–12.9	–3.1	1.7	7.0	11.2	10.1	5.3	0.7	–6.4	–16.1
15	–21.4	–19.9	–12.6	–2.8	1.9	7.2	11.2	10.0	5.1	0.6	–6.7	–16.2
16	–21.5	–19.7	–12.3	2.6	2.1	7.3	11.3	10.0	4.9	0.4	–6.9	–16.4
17	–21.5	–19.5	–12.0	–2.4	2.3	7.4	11.3	9.9	4.6	0.3	–7.3	–16.6
18	–21.5	–19.3	–11.8	–2.3	2.5	7.6	11.3	9.9	4.4	0.1	–7.6	–16.7
19	–21.6	–19.1	–11.5	–2.1	2.7	7.7	11.3	9.8	4.2	0.0	–8.0	–16.9
20	–21.6	–18.9	–11.2	–2.0	2.9	7.9	11.3	9.8	4.0	–0.2	–8.4	–17.0
21	–21.7	–18.7	–10.9	–1.9	3.1	8.0	11.3	9.7	3.8	–0.3	–8.7	–17.2
22	–21.7	–18.5	–10.7	–1.8	3.3	8.2	11.3	9.7	3.6	–0.5	–9.1	–17.4
23	–21.8	–18.3	–10.4	–1.7	3.5	8.4	11.3	9.6	3.5	–0.7	–9.5	–17.6
24	–21.8	–18.1	–10.1	–1.6	3.7	8.5	11.2	9.5	3.3	–0.9	–9.9	–17.8
25	–21.9	–17.9	–9.8	–1.5	3.9	8.7	11.2	9.4	3.1	–1.1	–10.3	–18.0
26	–21.9	–17.6	–9.4	–1.3	4.1	8.9	11.1	9.3	3.0	–1.3	–10.7	–18.2
27	–21.9	–17.4	–9.1	–1.2	4.2	9.0	11.0	9.1	2.9	–1.5	–11.1	–18.4
28	–21.8	–17.1	–8.7	–1.0	4.4	9.2	11.0	8.9	2.8	–1.8	–11.4	–18.7
29	–21.8		–8.3	–0.9	4.6	9.3	10.9	8.8	2.7	–2.0	–11.8	–18.9
30	–21.8		–8.0	–0.8	4.8	9.5	10.9	8.6	2.5	–2.3	–12.2	–19.2
31	–21.7		–7.6		4.9		10.9	8.4		–2.5		–19.4

Appendix A: Table 7
(continued)

Sept Iles Airport, Quebec

Daily Temperature Maximums (°C)

day of month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1	−8.2	−8.2	−4.3	1.3	7.1	13.9	18.9	19.9	16.7	10.5	4.8	−2.8
2	−8.3	−8.2	−4.1	1.5	7.3	14.1	19.0	19.9	16.5	10.3	4.6	−3.1
3	−8.4	−8.1	−3.9	1.7	7.4	14.3	19.1	19.9	16.3	10.1	4.4	−3.4
4	−8.6	−8.1	−3.7	1.9	7.6	14.5	19.2	19.9	16.1	9.9	4.2	−3.8
5	−8.7	−8.1	−3.5	2.0	7.8	14.7	19.3	19.8	15.9	9.7	3.9	−4.1
6	−8.8	−8.0	−3.3	2.2	8.0	14.9	19.4	19.8	15.8	9.5	3.7	−4.4
7	−8.9	−8.0	−3.1	2.4	8.3	15.1	19.5	19.8	15.5	9.3	3.5	−4.7
8	−8.9	−7.9	−2.9	2.6	8.5	15.4	19.6	19.7	15.3	9.2	3.2	−5.0
9	−8.9	−7.8	−2.7	2.8	8.7	15.6	19.7	19.6	15.1	9.0	3.0	−5.3
10	−8.9	−7.6	−2.5	3.0	9.0	15.8	19.8	19.5	14.9	8.9	2.7	−5.6
11	−8.9	−7.5	−2.4	3.2	9.2	16.0	19.8	19.4	14.7	8.7	2.5	−5.9
12	−8.9	−7.4	−2.2	3.4	9.5	16.2	19.9	19.3	14.5	8.5	2.2	−6.1
13	−8.8	−7.3	−2.0	3.7	9.7	16.5	20.0	19.2	14.3	8.4	2.0	−6.3
14	−8.8	−7.2	−1.8	3.9	9.9	16.7	20.0	19.1	14.1	8.2	1.7	−6.5
15	−8.8	−7.0	−1.6	4.1	10.2	16.9	20.0	19.0	13.9	8.0	1.5	−6.6
16	−8.7	−6.9	−1.4	4.3	10.5	17.1	20.1	18.9	13.7	7.8	1.3	−6.8
17	−8.7	−6.8	−1.2	4.5	10.7	17.3	20.1	18.8	13.5	7.7	1.1	−6.9
18	−8.6	−6.6	−1.1	4.7	11.0	17.4	20.1	18.8	13.3	7.5	0.8	−7.0
19	−8.6	−6.5	−0.9	4.9	11.2	17.6	20.1	18.7	13.1	7.3	0.6	−7.1
20	−8.5	−6.3	−0.7	5.0	11.4	17.7	20.1	18.6	12.9	7.1	0.4	−7.1
21	−8.5	−6.1	−0.5	5.1	11.6	17.9	20.1	18.4	12.7	7.0	0.2	−7.2
22	−8.4	−5.9	−0.3	5.3	11.9	18.0	20.1	18.3	12.5	6.8	0.0	−7.3
23	−8.4	−5.7	−0.2	5.5	12.1	18.1	20.1	18.2	12.3	6.6	−0.3	−7.4
24	−8.4	−5.5	0.0	5.7	12.3	18.2	20.0	18.1	12.1	6.4	−0.5	−7.4
25	−8.4	−5.3	0.1	5.9	12.4	18.3	20.0	17.9	11.9	6.3	−0.7	−7.5
26	−8.4	−5.1	0.3	6.1	12.6	18.4	20.0	17.8	11.7	6.1	−1.1	−7.5
27	−8.4	−4.9	0.5	6.3	12.8	18.5	20.0	17.6	11.5	5.8	−1.4	−7.6
28	−8.3	−4.6	0.6	6.5	13.1	18.6	19.9	17.4	11.3	5.6	−1.7	−7.8
29	−8.3		0.8	6.7	13.3	18.7	19.9	17.3	11.1	5.4	−2.1	−7.9
30	−8.3		1.0	6.9	13.5	18.8	19.9	17.1	10.8	5.2	−2.4	−8.0
31	−8.2		1.1		13.7		19.9	16.9		5.0		−8.1

Appendix A: Table 7
(continued)

Sept Iles Airport, Quebec

Daily Temperature Minimums (°C)

day of month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1	–18.3	–19.4	–15.4	–7.4	–1.2	4.1	9.4	10.8	7.2	1.9	–3.0	–11.5
2	–18.5	–19.4	–15.2	–7.1	–1.0	4.3	9.6	10.7	7.0	1.7	–3.1	–11.9
3	–18.6	–19.4	–15.0	–6.9	–0.9	4.5	9.8	10.7	6.9	1.5	–3.2	–12.3
4	–18.8	–19.4	–14.8	–6.6	–0.7	4.7	10.0	10.6	6.7	1.4	–3.3	–12.7
5	–19.0	–19.4	–14.6	–6.3	–0.6	4.8	10.1	10.6	6.5	1.2	–3.4	–13.1
6	–19.1	–19.4	–14.4	–6.1	–0.4	5.0	10.3	10.6	6.4	1.0	–3.6	–13.5
7	–19.3	–19.3	–14.2	–5.8	–0.2	5.2	10.4	10.5	6.2	0.9	–3.8	–14.0
8	–19.4	–19.1	–14.0	–5.6	–0.1	5.4	10.5	10.4	5.9	0.7	–4.0	–14.3
9	–19.4	–19.0	–13.7	–5.3	0.1	5.6	10.5	10.2	5.7	0.6	–4.3	–14.7
10	–19.5	–18.8	–13.4	–5.1	0.3	5.8	10.6	10.1	5.5	0.4	–4.5	–15.0
11	–19.5	–18.7	–13.1	–4.9	0.4	6.0	10.7	10.0	5.3	0.2	–4.7	–15.3
12	–19.5	–18.5	–12.9	–4.6	0.6	6.2	10.7	9.8	5.1	0.1	–5.0	–15.6
13	–19.5	–18.4	–12.6	–4.4	0.7	6.4	10.8	9.7	4.9	–0.1	–5.3	–15.8
14	–19.5	–18.2	–12.3	–4.2	0.9	6.6	10.9	9.6	4.7	–0.3	–5.6	–16.0
15	–19.5	–18.1	–12.1	–4.0	1.1	6.9	10.9	9.5	4.5	–0.5	–5.9	–16.2
16	–19.5	–17.9	–11.8	–3.8	1.3	7.1	11.0	9.3	4.4	–0.6	–6.2	–16.4
17	–19.5	–17.8	–11.6	–3.6	1.5	7.3	11.0	9.2	4.2	–0.8	–6.5	–16.5
18	–19.5	–17.6	–11.3	–3.4	1.6	7.4	11.0	9.1	4.0	–1.0	–6.8	–16.7
19	–19.5	–17.5	–11.0	–3.2	1.8	7.5	11.0	8.9	3.9	–1.2	–7.1	–16.8
20	–19.5	–17.3	–10.6	–3.0	2.0	7.7	11.1	8.8	3.7	–1.4	–7.4	–16.9
21	–19.4	–17.1	–10.3	–2.9	2.1	7.9	11.1	8.7	3.6	–1.5	–7.7	–16.9
22	–19.4	–16.9	–10.0	–2.8	2.3	8.0	11.1	8.6	3.5	–1.7	–8.0	–17.0
23	–19.4	–16.8	–9.7	–2.6	2.5	8.2	11.1	8.5	3.4	–1.8	–8.3	–17.1
24	–19.4	–16.6	–9.5	–2.4	2.6	8.3	11.1	8.4	3.2	–2.0	–8.6	–17.1
25	–19.4	–16.3	–9.2	–2.3	2.8	8.5	11.1	8.3	3.0	–2.1	–8.9	–17.2
26	–19.4	–16.1	–9.0	–2.1	3.0	8.6	11.1	8.1	2.9	–2.3	–9.3	–17.3
27	–19.4	–15.9	–8.7	–1.9	3.2	8.8	11.1	8.0	2.7	–2.4	–9.7	–17.4
28	–19.4	–15.7	–8.4	–1.8	3.4	8.9	11.0	7.8	2.5	–2.5	–10.2	–17.6
29	–19.4		–8.2	–1.6	3.6	9.1	11.0	7.7	2.3	–2.6	–10.6	–17.8
30	–19.4		–7.9	–1.4	3.7	9.2	10.9	7.5	2.1	–2.7	–11.0	–17.9
31	–19.4		–7.7		3.9		10.9	7.3		–2.9		–18.1

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Appendix C

Computer Programs

All subroutines which are common to more than one program are listed at the end of this appendix

```
c      NPP.FOR
c      program to compute npp from climate data
c      september 29,1988
c      revised january 27,1989
c
       integer state,id,type,maxt(365),mint(365),avgt(365),
      $error,key(91),count,len(12)
       real cmaxt(365),cmint(365),cavgt(365)
       open(10,file='climate.dat',status='old')
       open(12,file='newnpp.dat',status='new')
       open(13,file='stalat.dat',status='old')
       open(14,file='nppplt.dat',status='new')
       open(15,file='cantemp.dat'.status='old')
       open(16,file='gslen.dat',status='new')
       data len/31,28.31,30,31,30,31,31,30,31,30,31/
c
c      read in climate normals
c
       count=0
       do i=1,167
          read(10.50)state,id,type,(maxt(j),j=1,365)
             count=count+1
             read(10,50)state,id,type,(mint(j),j=1,365)
             read(10,50)state,id,type,(avgt(j),j=1,365)
             read(10,60)ii .
50           format(1x,i2,i4,i1,365i3)
60           format(1x,i1)
             do j=1,365
                cmaxt(j)=float(maxt(j)-32)*(5./9.)
                cmint(j)=float(mint(j)-32)*(5./9.)
                cavgt(j)=float(avgt(j)-32)*(5./9.)
             enddo
             write(*,70)state,id
70           format(' calling mainprog, id no: ',i2,i4)
             call mainprog(cmaxt,cmint,cavgt,state,id,error,
      $        count,lat1,lat2)
          if(error.eq.1) goto 500
       enddo
       do i=1,6
          count=count+1
          read(15,80)state,id,lat1,lat2
80        format(i2,i4.2(1x,i2))
```

```
        read(15,*)(cmaxt(j),j=1,365)
        read(15,*)(cmint(j),j=1,365)
        do k=1,365
          cavgt(k)=(cmaxt(k)+cmint(k))/2.0
        enddo
        call mainprog(cmaxt,cmint,cavgt,state,id,error,
     $       count,lat1,lat2)
      enddo
500   stop
      end


      subroutine mainprog(cmaxt,cmint,cavgt,state,id,error,
     $count,lat1,lat2)

      integer staid,state,gsnet(3),type,gs,dd,df(3),ds(3),
     $error,count
      real newavg(365),lat,lai(3),laiful(3),newmax(365)
     $,newmin(365),kv(3),et(3),totet(3),c(3)
      dimension cmaxt(365),cmint(365),cavgt(365),npp(3)
      data laiful/1.0,1.0,1.0/
      data kv/0.36,0.66,0.31/
      staid=(state*10000)+id
      error=0
      alpha1=.003
      if(state.ne.51) then
        read(13,*)idsta,lat1,lat2
        if(idsta.ne.staid) then
          write(*,100)staid,idsta
100       format(1x,'error in id weather data= ',i5,
     $       ' and npp data= ',i5)
          error=1
          goto 1000
        endif
      endif
      lat=float(lat1)+(float(lat2)/60.)
      do i=1,365
        newmax(i)=cmaxt(i)
        newmin(i)=cmint(i)
        newavg(i)=cavgt(i)
      enddo
      gs=0
      do k=1,3
        gsnet(k)=0
        totet(k)=0
        ds(k)=0
        df(k)=0
      enddo
      dd=0
      totpe=0
      do i=1,365
```

```
          call getpe(i,lat,newavg(i),daype)
          do type=1,3
             if ((type.eq.1).or.(type.eq.3)) then
                lai(type)=laiful(type)
                call getc(type,newmax(i),newmin(i),newavg(i),c(type))
                if(c(type).ne.0) df(type)=df(type)+1
             else
                c(type)=1.0
                call getlai(gs,dd,lat,newavg(i),pct,i,df(type),
     $ds(type))
                lai(type)=laiful(2)*pct
             endif
             et(type)=daype*c(type)*lai(type)
             totet(type)=totet(type)+et(type)
          enddo
          totpe=daype+totpe
       enddo
       do m=1,3
          gsnet(m)=df(m)—ds(m)
          npp(m)=nint(kv(m)*alpha1*25400.*totet(m))
       enddo
       write (12,800) staid,lat,(npp(k),k=1,3),
     $(gsnet(k),k=1,3),totpe,(totet(k),k=1,3)
800    format (1x,i6,1x,f5.2,3(i5,1x),3(i3,1x),4(f7.2,1x))
       write(16,900) staid,gsnet(2),ds(2),df(2)
900    format(4(1x,i6))
       write(14,950)lat,(npp(k),k=1,3)
950    format(1x,f5.2,3(1x,i4))
1000   return
       end
```

Appendix C (continued)

```
c       KCALC.FOR
c       program to compute k from npp and climate data
c       september 23,1988
c       revised 1/23/89 to correct pe calculations
c       revised 4/17/89 to correct hamon factor and fall color change
c
        integer staid,type,maxt(365),mint(365),avgt(365),records(8),error
        real cmaxt(365),cmint(365),cavgt(365)
        data records/9,3,1,11,2,1,3,1/
        open(10,file='nppsta.dat',status='old')
        open(11,file='npp.dat',status='old')
        open(15,file='k.dat',status='new')
c
c       read in climate normals
c
        do i=1,8
          read(10,50)staid,type,(maxt(j),j=1,365)
          read(10,50)staid,type,(mint(j),j=1,365)
          read(10,50)staid,type,(avgt(j),j=1,365)
50        format(1x,i6,i1,365i3)
          do j=1,365
            cmaxt(j)=float(maxt(j)-32)*(5./9.)
            cmint(j)=float(mint(j)-32)*(5./9.)
            cavgt(j)=float(avgt(j)-32)*(5./9.)
          enddo
          do k=1,records(i)
            call mainprog(i,cmaxt,cmint,cavgt,staid,error)
            if(error.eq.1) goto 500
          enddo
        enddo
500     stop
        end


        subroutine mainprog(loop,cmaxt,cmint,cavgt,staid,error)

        integer staid,gsnet,type,selev,welev,gs,dd,df,ds,error
        real newavg(365),lat,lai,laiful(3),newmax(365),newmin(365)
       $,klow,khigh
        dimension cmaxt(365),cmint(365),cavgt(365)
        data laiful/1.0,1.0,1.0/
c        data laiful/8.8,5.25,7.8/
        error=0
        gsnet=0
        alpha1=.003
        alpha2=.005
        read(11,*)idno,idsta,type,selev,welev,lat1,lat2,npp
        if(idsta.ne.staid) then
          write(*,100)staid,idsta
100       format(1x,'error in id weather data= ',i5,' and npp data= ',i5)
          error=1
```

```
          goto 1000
        endif
        lat=float(lat1)+(float(lat2)/60.)
        if(selev.ne.0) then
c           write(*,200)selev,welev
200       format(1x,'going to dolapse,',2(1x,i4))
          call dolapse(cmaxt,cmint,cavgt,newmax,newmin,newavg,selev,welev)
        else
          do i=1,365
            newmax(i)=cmaxt(i)
            newmin(i)=cmint(i)
            newavg(i)=cavgt(i)
          enddo
        endif
        totet=0
        gs=0
        dd=0
        ds=0
        df=0
        totpe=0
        do i=1,365
          call getpe(i,lat,newavg(i),daype)
          if ((type.eq.1).or.(type.eq.3)) then
            lai=laiful(type)
            call getc(type,newmax(i),newmin(i),newavg(i),c)
            if(c.ne.0) df=df+1
          else
            c=1.0
            call getlai(gs,dd,lat,newavg(i),pct,i,df,ds)
            lai=laiful(2)*pct
          endif
          et=daype*c*lai
          totpe=daype+totpe
          totet=totet+et
        enddo
        gsnet=df—ds
        khigh=float(npp)/(alpha1*25400.*totet)
        klow=float(npp)/(alpha2*25400.*totet)
        write (15,800) idno,lat1,lat2,selev,npp,gsnet,type,totpe,
       $totet,khigh,klow
800     format (1x,3(i2,1x),2(i4,1x),i3,1x,i1,1x,4(f7.2,1x))
1000    return
        end
```

```
c       BUDBRK.FOR
c       program to compute elapsed degree days
        real ctemp(152),nulat(31)
        integer maxt(31),mint(31),degday(31),avgt(31),dd,len(5)
        data len /31,28,31,30,31/
        open(unit=10,file='maxmin.dat',status='old')
        open(unit=12,file='budday.dat',status='old')
        open(unit=14,file='budplt.dat',status='new')
        do id=1,31
          len(2)=28
          ict=0
          degday(id)=0
          read(10,*) idno,itype,leap
          if (leap.eq.1) len(2)=29
          do n=1,5
            if (itype.eq.0) then
              read(10,*)(maxt(j),j=1,len(n))
              read(10,*)(mint(j),j=1,len(n))
              do l=1,len(n)
                if (mint(l).gt.maxt(l)) then
                  write(*,50) id,n,l
50                format('error in id ',i2,', month ',i1,', day ',i2)
                endif
                avgt(l)=(maxt(l)+mint(l))/2
              enddo
            else
              read(10,*)(avgt(j),j=1,len(n))
            endif
            do l=1,len(n)
              ict=ict+1
              ctemp(ict)=(float(avgt(l))-32.0)*5.0/9.0
            enddo
          enddo
          read(12,*) id2,lat1,lat2,long1,long2,julday
          nulat(id)=float(lat1)+(float(lat2)/60.0)
          nst=32
          do m=nst,julday
            if (ctemp(m).gt.5.0) then
              dd=nint(ctemp(m)-5.0)
              degday(id)=degday(id)+dd
            else
            endif
          enddo
        enddo
        write(14,100)
100     format(1x,'31  1  1')
        write(14,200)(nulat(j),j=1,16)
200     format(16(1x,f5.2))
        write(14,300)(nulat(j),j=17,31)
300     format(15(1x,f5.2))
        write(14,400)(degday(j),j=1,31)
```

Appendix C (continued)

```
400     format(31(1x,i3))
        stop
        end
```

```
c       DAILY.FOR
c       program to compute npp from climate data
c       september 29,1988
c       revised december 28,1988 to compute daily et for plotting
c       4/18/89 plot daily npp data; all revisions to date
c       for two stations only for decid&boreal (122738 & 512582)
c
        integer state,id,type,maxt(365),mint(365),avgt(365),
       $error,key(91),precip(365)
        real cmaxt(365),cmint(365),cavgt(365)
        open(10,file='climate.dat',status='old')
        open(14,file='cantemp.dat',status='old')
c
c       read in climate normals
c
        do i=1,167
          read(10,50)state,id,type,(maxt(j),j=1,365)
          read(10,50)state,id,type,(mint(j),j=1,365)
          read(10,50)state,id,type,(avgt(j),j=1,365)
          read(10,50)state,id,type,(precip(j),j=1,365)
50        format(1x,i2,i4,i1,365i3)
          idsta=state*10000+id
          if(idsta.eq.122738) then
            do j=1,365
              cmaxt(j)=float(maxt(j)-32)*(5./9.)
              cmint(j)=float(mint(j)-32)*(5./9.)
              cavgt(j)=float(avgt(j)-32)*(5./9.)
            enddo
            lat1=38
            lat2=3
            write(*,70)state,id
70          format(' calling mainprog, id no: ',i2,i4)
            call mainprog(cmaxt,cmint,cavgt,state,id,
       $      lat1,lat2)
          else
          endif
        enddo
        do i=1,6
          read(14,80)state,id,lat1,lat2
80        format(i2,i4,2(1x,i2))
          read(14,*)(cmaxt(j),j=1,365)
          read(14,*)(cmint(j),j=1,365)
          idsta=state*10000+id
          if(idsta.eq.512582) then
            do k=1,365
              cavgt(k)=(cmaxt(k)+cmint(k))/2.0
            enddo
            call mainprog(cmaxt,cmint,cavgt,state,id,
       $      lat1,lat2)
          else
          endif
```

```
  enddo
  stop
  end


  subroutine mainprog(cmaxt,cmint,cavgt,state,id,
$lat1,lat2)

  integer staid,state,type,gs,dd,df(3),ds(3),error
  real newavg(365),lat,lai(3),laiful(3),newmax(365)
$,newmin(365),kv(3),et(3),totnpp(3),c(3),totet(3),
$daily(365,3)
  character*11 plotfile
  dimension cmaxt(365),cmint(365),cavgt(365)
  data laiful/1.0,1.0,1.0/
  data kv/0.36,0.66,0.31/
  staid=(state*10000)+id
  alpha1=.003
  do i=1,365
    newmax(i)=cmaxt(i)
    newmin(i)=cmint(i)
    newavg(i)=cavgt(i)
  enddo
  gs=0
  do k=1,3
    totet(k)=0
    totnpp(k)=0
    ds(k)=0
    df(k)=0
  enddo
  dd=0
  lat=float(lat1)+(float(lat2)/60.0)
  do i=1,365
    daily(i,1)=float(i)
    call getpe(i,lat,newavg(i),daype)
    do type=1,3
      if ((type.eq.1).or.(type.eq.3)) then
        lai(type)=laiful(type)
        call getc(type,newmax(i),newmin(i),newavg(i),c(type))
        if(c(type).ne.0) df(type)=df(type)+1
      else
        c(type)=1.0
        call getlai(gs,dd,lat,newavg(i),pct,i,df(type),
$ds(type))
        lai(type)=laiful(2)*pct
      endif
      et(type)=daype*c(type)*lai(type)
    enddo
    do m=1,2
      j=m+1
      totet(m)=et(m)+totet(m)
```

```
          daily(i,j)=et(m)*kv(m)*alpha1*25400.
          totnpp(m)=totnpp(m)+daily(i,j)
        enddo
      enddo
      testnpp1=totet(1)*kv(1)*alpha1*25400.
      testnpp2=totet(2)*kv(2)*alpha1*25400.
      if(staid.eq.122738) then
        plotfile='southdy.dat'
      else
        plotfile='northdy.dat'
      endif
      open(unit=16,file=plotfile,status='new')
      do i=1,365
        iday=int(daily(i,1))
        write(16,950)iday,(daily(i,j),j=2,3)
950     format(1x,i3,2(1x,f6.3))
      enddo
      close(16)
      write(*,975)totnpp(1),totnpp(2)
      write(*,975)testnpp1,testnpp2
975   format(2(1x,f10.3))
      return
      end
```

```
c     RUNOFF.FOR
c     program to compute seasonal runoff from climate data
c     september 29,1988
c     revised december 21,1988 to compute s nought
c     revised feb 5
c     revised feb 7 (include off—season precip)
c     revised 4/23/89 to include all changes to date
c
      integer state,id,type,maxt(365),mint(365),avgt(365),
     $error,count,precip(365)
      real cmaxt(365),cmint(365),cavgt(365)
      open(10,file='climate.dat',status='old')
      open(13,file='stalat.dat',status='old')
      open(15,file='runoff.dat',status='new')
      open(16,file='gamma.dat',status='new')
c
c     read in climate normals
c
      count=0
      do i=1,167
         read(10,50)state,id,type,(maxt(j),j=1,365)
         count=count+1
         read(10,50)state,id,type,(mint(j),j=1,365)
         read(10,50)state,id,type,(avgt(j),j=1,365)
         read(10,50)state,id,type,(precip(j),j=1,365)
50       format(1x,i2,i4,i1,365i3)
         do j=1,365
            cmaxt(j)=float(maxt(j)—32)*(5./9.)
            cmint(j)=float(mint(j)—32)*(5./9.)
            cavgt(j)=float(avgt(j)—32)*(5./9.)
         enddo
         write(*,70)state,id
70       format(' calling mainprog, id no: ',i2,i4)
         call mainprog(cmaxt,cmint,cavgt,state,id,error,
     $        count,precip)
         if(error.eq.1) goto 500
      enddo
500   stop
      end


      subroutine mainprog(cmaxt,cmint,cavgt,state,id,error,
     $count,precip)

      integer staid,state,gsnet(3),type,gs,dd,df(3),ds(3),
     $error,count,precip(365),count2
      real newavg(365),lat,lai(3),laiful(3),newmax(365)
     $,newmin(365),kv(3),et(3),totet(3),c(3),intercept
     $,runoff(3),seaspe(3),seaspr(3),avgpe(3),avgpr(3)
      dimension cmaxt(365),cmint(365),cavgt(365),a(3),b(3),
     $e(3),d(3),factor(3)
```

```
      data laiful/1.0,1.0,1.0/
      data kv/0.36,0.66,0.31/
      data a/0.0,0.036,0.03/
      data b/0.0,0.083,0.17/
      data e/0.0,0.02,0.03/
      data d/0.0,0.059,0.17/
      staid=(state*10000)+id
      error=0
      psec=5.0
      rkappa=0.56
      read(13,*)idsta,lat1,lat2
      if(idsta.ne.staid) then
        write(*,100)staid,idsta
100     format(1x,'error in id weather data= ',i5,' and npp data= ',i5)
        error=1
        goto 1000
      endif
      lat=float(lat1)+(float(lat2)/60.)
      cond=(30.77—0.78*lat)*24.0
      if (lat.lt.38.0) then
        do i=1,365
          newmax(i)=cmaxt(i)
          newmin(i)=cmint(i)
          newavg(i)=cavgt(i)
        enddo
        gs=0
        totpr=0
        do k=1,3
          gsnet(k)=0
          totet(k)=0
          ds(k)=0
          df(k)=0
          seaspe(k)=0
          seaspr(k)=0
        enddo
        dd=0
        totpe=0
        do i=1,365
          totpr=totpr+(float(precip(i))/100.0)
          call getpe(i,lat,newavg(i),daype)
          do type=1,3
            if ((type.eq.1).or.(type.eq.3)) then
              lai(type)=laiful(type)
              call getc(type,newmax(i),newmin(i),newavg(i),c(type))
              if(c(type).ne.0) df(type)=df(type)+1
            else
              c(type)=1.0
              call getlai(gs,dd,lat,newavg(i),pct,i.df(type),
     $          ds(type))
              lai(type)=laiful(2)*pct
            endif
```

```
               et(type)=daype*c(type)*lai(type)
               totet(type)=totet(type)+et(type)
            enddo
            totpe=daype+totpe
            if(gs.eq.1) then
               seaspe(2)=seaspe(2)+daype
               seaspr(2)=seaspr(2)+(float(precip(i))/100.0)
            endif
            if(c(3).ne.0.) then
               seaspe(3)=seaspe(3)+daype
               seaspr(3)=seaspr(3)+(float(precip(i))/100.0)
            endif
         enddo
         do m=2,3
            gsnet(m)=df(m)—ds(m)
            rlambda=50.18/totpr
            si=rlambda*a(m)/(1.0—b(m))
            call mdgam(si,rkappa,gam,ier)
            if(ier.ne.0) write(*,*) 'error in gamma'
            par1=gamma(rkappa)
            par2=par1—gam*par1
            rkplus=rkappa+1.0
            par6=gamma(rkplus)
            call mdgam(si,rkplus,gam.ier)
            if(ier.ne.0) write(*,*) 'error in gamma'
            par3=par6—gam*par6
            par4=rkappa*(par1**2)
            par5=(1.0—b(m))*par3
            par7=a(m)*rlambda*par2
            factor(m)=(par2/par4)*(par5—par7)
            effpre=seaspr(2)*factor(m)
            runoff(m)=(effpre—seaspe(2)*kv(m))*2.54
c            bracket=(effpre+prengs—(kv(m)*seaspe(m)))/(cond*365.0)
c            if (bracket.lt.0.0) then
c               seas(count2,m)=0.0
c            else
c               seas(count2.m)=bracket**(1.0/psec)
c            endif
         enddo
c         write(15,950)staid,totpr,
c    $       cond,seas(count2,2),seas(count2,3),
c    $       lat,seaspr(2),seaspr(3).seaspe(2),seaspe(3)
c950     format(1x,i6,1x,9(f8.2.1x))
         write(15,900)lat,(runoff(m),m=2,3)
900      format(3(1x,f7.2))
         write(16,950)id,lat,rlambda,(factor(m),m=2,3),
     $      seaspr(2),seaspe(2),(runoff(m),m=2,3)
950      format(1x,i6,2(1x,f5.2),2(1x.f4.2),4(1x,f6.2))
      endif
1000  return
      end
```

```
c       NEWSO3.FOR
c       program to compute s nought
c       this version for entire year, both types
c       revised 4/26/89 to include all changes to date
c
        integer state,id,type,maxt(365),mint(365),avgt(365),
       $error,count,precip(365)
        real cmaxt(365),cmint(365),cavgt(365)
        open(10,file='climate.dat',status='old')
        open(13,file='stalat.dat',status='old')
        open(15,file='soallyr.dat',status='new')
c
c       read in climate normals
c
        count=0
        do i=1,167
          read(10,50)state,id,type,(maxt(j),j=1,365)
          count=count+1
          read(10,50)state,id,type,(mint(j),j=1,365)
          read(10,50)state,id,type,(avgt(j),j=1,365)
          read(10,50)state,id,type,(precip(j),j=1,365)
50        format(1x,i2,i4,i1,365i3)
          do j=1,365
            cmaxt(j)=float(maxt(j)-32)*(5./9.)
            cmint(j)=float(mint(j)-32)*(5./9.)
            cavgt(j)=float(avgt(j)-32)*(5./9.)
          enddo
          write(*,70)state,id
70        format(' calling mainprog, id no: ',i2,i4)
          call mainprog(cmaxt,cmint,cavgt,state,id,error,
       $      count,precip)
          if(error.eq.1) goto 500
        enddo
500     stop
        end


        subroutine mainprog(cmaxt,cmint,cavgt,state,id,error,
       $count,precip)

        integer staid,state,gsnet(3),type,gs,dd,df(3),ds(3),
       $error,count,precip(365),count2,gsnot
        real newavg(365),lat,lai(3),laiful(3),newmax(365)
       $,newmin(365),kv(3),et(3),totet(3),c(3),intercept
       $,runoff(3),seaspe(3),seaspr(3),avgpe(3),avgpr(3)
        dimension cmaxt(365),cmint(365),cavgt(365),a(3),b(3),
       $e(3),d(3),factor(3),so(3)
        data laiful/1.0,1.0,1.0/
        data kv/0.36,0.66,0.31/
        data a/0.0,0.036,0.03/
        data b/0.0,0.083,0.17/
```

```
      data e/0.0,0.02,0.03/
      data d/0.0,0.059,0.17/
      staid=(state*10000)+id
      error=0
      psec=5.0
      rkappa=0.56
      read(13,*)idsta,lat1,lat2
      if(idsta.ne.staid) then
        write(*,100)staid,idsta
100     format(1x,'error in id weather data= ',i5,' and npp data= ',i5)
        error=1
        goto 1000
      endif
      lat=float(lat1)+(float(lat2)/60.)
      cond=(30.77-0.78*lat)*24.0
      if (lat.lt.38.0) then
        do i=1,365
          newmax(i)=cmaxt(i)
          newmin(i)=cmint(i)
          newavg(i)=cavgt(i)
        enddo
        gs=0
        totpr=0
        do k=1,3
          gsnet(k)=0
          totet(k)=0
          ds(k)=0
          df(k)=0
          seaspe(k)=0
          seaspr(k)=0
        enddo
        dd=0
        totpe=0
        do i=1,365
          totpr=totpr+(float(precip(i))/100.0)
          call getpe(i,lat,newavg(i),daype)
          do type=1,3
            if ((type.eq.1).or.(type.eq.3)) then
              lai(type)=laiful(type)
              call getc(type,newmax(i),newmin(i),newavg(i),c(type))
              if(c(type).ne.0) df(type)=df(type)+1
            else
              c(type)=1.0
              call getlai(gs,dd,lat,newavg(i),pct,i,df(type),
     $          ds(type))
              lai(type)=laiful(2)*pct
            endif
            et(type)=daype*c(type)*lai(type)
            totet(type)=totet(type)+et(type)
          enddo
          totpe=daype+totpe
```

```
   if(gs.eq.1) then
      seaspe(2)=seaspe(2)+daype
      seaspr(2)=seaspr(2)+(float(precip(i))/100.0)
   endif
   if(c(3).ne.0.) then
      seaspe(3)=seaspe(3)+daype
      seaspr(3)=seaspr(3)+(float(precip(i))/100.0)
   endif
enddo
gsnet(2)=df(2)-ds(2)+17
gsnet(3)=df(3)-ds(3)
do m=2,3
   rlambda=50.18/totpr
   si=rlambda*a(m)/(1.0-b(m))
   call mdgam(si,rkappa,gam,ier)
   if(ier.ne.0) write(*,*) 'error in gamma'
   par1=gamma(rkappa)
   par2=par1-gam*par1
   rkplus=rkappa+1.0
   par6=gamma(rkplus)
   call mdgam(si,rkplus,gam,ier)
   if(ier.ne.0) write(*,*) 'error in gamma'
   par3=par6-gam*par6
   par4=rkappa*(par1**2)
   par5=(1.0-b(m))*par3
   par7=a(m)*rlambda*par2
   factor(m)=(par2/par4)*(par5-par7)
   effpre=seaspr(m)*factor(m)
   runoff(m)=effpre-(totet(m)*kv(m))
   offpr=totpr-seaspr(m)
   gsnot=365-gsnet(m)
   if(gsnot.le.0.0) then
      prengs=0.0
   else
      si=rlambda*e(m)/(1.0-d(m))
      call mdgam(si,rkappa,gam,ier)
      if(ier.ne.0) write(*,*) 'error in gamma'
      par1=gamma(rkappa)
      par2=par1-gam*par1
      rkplus=rkappa+1.0
      par6=gamma(rkplus)
      call mdgam(si,rkplus,gam,ier)
      if(ier.ne.0) write(*,*) 'error in gamma'
      par3=par6-gam*par6
      par4=rkappa*(par1**2)
      par5=(1.0-d(m))*par3
      par7=e(m)*rlambda*par2
      factor(m)=(par2/par4)*(par5-par7)
      prengs=offpr*factor(m)
   endif
   bracket=(runoff(m)+prengs)/(365.*cond)
```

```
          if (bracket.lt.0.0) then
             so(m)=0.0
          else
             so(m)=bracket**(1.0/psec)
          endif
       enddo
       write(15,950)lat,so(2),so(3)
950    format(3(1x,f8.3))
    endif
1000 return
    end
```

```
c       NEWSO4.FOR
c       program to compute s nought
c       this version for entire year, both types
c       including evaporation and precipitation
c       revised 4/26/89 to include all changes to date
c
        integer state,id,type,maxt(365),mint(365),avgt(365),
       $error,count,precip(365)
        real cmaxt(365),cmint(365),cavgt(365)
        open(10,file='climate.dat',status='old')
        open(13,file='stalat.dat',status='old')
        open(15,file='soallyr2.dat',status='new')
        open(16,file='soinput.dat',status='new')
c
c       read in climate normals
c
        count=0
        do i=1,167
          read(10,50)state,id,type,(maxt(j),j=1,365)
          count=count+1
          read(10,50)state,id,type,(mint(j),j=1,365)
          read(10,50)state,id,type,(avgt(j),j=1,365)
          read(10,50)state,id,type,(precip(j),j=1,365)
50        format(1x,i2,i4,i1,365i3)
          do j=1,365
            cmaxt(j)=float(maxt(j)-32)*(5./9.)
            cmint(j)=float(mint(j)-32)*(5./9.)
            cavgt(j)=float(avgt(j)-32)*(5./9.)
          enddo
          write(*,70)state,id
70        format(' calling mainprog, id no: ',i2,i4)
          call mainprog(cmaxt,cmint,cavgt,state,id,error,
       $        count,precip)
          if(error.eq.1) goto 500
        enddo
500     stop
        end


        subroutine mainprog(cmaxt,cmint,cavgt,state,id,error,
       $count,precip)

        integer staid,state,gsnet(3),type,gs,dd,df(3),ds(3),
       $error,count,precip(365),count2,gsnot
        real newavg(365),lat,lai(3),laiful(3),newmax(365)
       $,newmin(365),kv(3),et(3),totet(3),c(3),
       $runoff(3),seaspe(3),seaspr(3),oldeff(100),oldso(100)
        dimension cmaxt(365),cmint(365),cavgt(365),a(3),b(3),
       $e(3),d(3),factor(4),so(3),eff(3)
        logical done
        data laiful/1.0,1.0,1.0/
```

```
      data kv/0.36,0.66,0.31/
      data a/0.0,0.036,0.03/
      data b/0.0,0.083,0.17/
      data e/0.0,0.02,0.03/
      data d/0.0,0.059,0.17/
      staid=(state*10000)+id
      error=0
      read(13,*)idsta,lat1,lat2
      if(idsta.ne.staid) then
        write(*,100)staid,idsta
100     format(1x,'error in id weather data= ',i5,' and npp data= ',i5)
        error=1
        goto 1000
      endif
      lat=float(lat1)+(float(lat2)/60.)
      if (lat.lt.38.0) then
        psec=5.0
        rkappa=0.56
        cond=(30.77-0.78*lat)*24.0
        pi=3.1415926535
        psed=(psec+1.0)/2.0
        psem=2.0/(psec-3.0)
        poros=0.4
        visc=6.1E-11
        beta=0.26
        st=1.17E-2
        phie=0.11
        diffe=10.0**(0.66+0.55/psem+0.14/(psem**2))
        condint=visc*cond
        suct=st*sqrt(poros/(condint*diffe))
        do i=1,365
          newmax(i)=cmaxt(i)
          newmin(i)=cmint(i)
          newavg(i)=cavgt(i)
        enddo
        gs=0
        totpr=0
        do k=1,3
          gsnet(k)=0
          totet(k)=0
          ds(k)=0
          df(k)=0
          seaspe(k)=0
          seaspr(k)=0
        enddo
        dd=0
        totpe=0
        do i=1,365
          totpr=totpr+(float(precip(i))/100.0)
          call getpe(i,lat,newavg(i),daype)
          do type=1,3
```

```
          if ((type.eq.1).or.(type.eq.3)) then
             lai(type)=laiful(type)
             call getc(type,newmax(i),newmin(i),newavg(i),c(type))
             if(c(type).ne.0) df(type)=df(type)+1
          else
             c(type)=1.0
             call getlai(gs,dd,lat,newavg(i),pct,i,df(type),
$               ds(type))
             lai(type)=laiful(2)*pct
          endif
          et(type)=daype*c(type)*lai(type)
          totet(type)=totet(type)+et(type)
       enddo
       totpe=daype+totpe
       if(gs.eq.1) then
          seaspe(2)=seaspe(2)+daype
          seaspr(2)=seaspr(2)+(float(precip(i))/100.0)
       endif
       if(c(3).ne.0.) then
          seaspe(3)=seaspe(3)+daype
          seaspr(3)=seaspr(3)+(float(precip(i))/100.0)
       endif
    enddo
    gsnet(2)=df(2)—ds(2)+17
    gsnet(3)=df(3)—ds(3)
    do m=2,3
       l1=(2*m)—3
       l2=l1+1
       effect=0.0
       done=.false.
       soold=0.0
       rlambda=50.18/totpr
       si=rlambda*a(m)/(1.0—b(m))
       call mdgam(si.rkappa,gam.ier)
       if(ier.ne.0) write(*,*) 'error in gamma'
       par1=gamma(rkappa)
       par2=par1—gam*par1
       rkplus=rkappa+1.0
       par6=gamma(rkplus)
       call mdgam(si,rkplus,gam,ier)
       if(ier.ne.0) write(*,*) 'error in gamma'
       par3=par6—gam*par6
       par4=rkappa*(par1**2)
       par5=(1.0—b(m))*par3
       par7=a(m)*rlambda*par2
       factor(l1)=(par2/par4)*(par5—par7)
       effpre=seaspr(m)*factor(l1)
       runoff(m)=effpre—(totet(m)*kv(m))
       gsnot=365—gsnet(m)
       if(gsnot.le.0.0) then
          prengs=0.0
```

```
          pengs=0.0
          factor(l2)=00.0
        else
          offpr=totpr—seaspr(m)
          offpe=totpe—seaspe(m)
          pengs=0.0
          avgpe=offpe/float(gsnot)
          si=rlambda*e(m)/(1.0—d(m))
          call mdgam(si,rkappa,gam,ier)
          if(ier.ne.0) write(*,*) 'error in gamma'
          par1=gamma(rkappa)
          par2=par1—gam*par1
          rkplus=rkappa+1.0
          par6=gamma(rkplus)
          call mdgam(si,rkplus,gam,ier)
          if(ier.ne.0) write(*,*) 'error in gamma'
          par3=par6—gam*par6
          par4=rkappa*(par1**2)
          par5=(1.0—d(m))*par3
          par7=e(m)*rlambda*par2
          factor(l2)=(par2/par4)*(par5—par7)
          prengs=offpr*factor(l2)
        endif
        nct=0
        mct=0
        do while (.not.done)
          nct=nct+1
          ict=(mct*25)+nct
          bracket=(runoff(m)+prengs—pengs)/(365.*cond)
          if (bracket.lt.0.0) then
            so(m)=0.0
          else
            so(m)=bracket**(1.0/psec)
          endif
          tol=abs(so(m)—soold)
          if(so(m).eq.0.0) tol=0.0
          if((gsnot.le.0.0).or.(tol.lt.0.0009)) then
            done=.true.
            eff(m)=effect
          else
            if((nct.lt.25).and.(mct.lt.4)) then
              soold=so(m)
              oldso(ict)=so(m)
              effect=((2.0*beta*poros*cond*suct)/
$               (pi*psem*(avgpe**2)))*phie*
$               (so(m)**(psed+2.0))
              oldeff(ict)=effect
              if (effect.ge.0.6366197) then
                pengs=offpe
              else
                pengs=sqrt((pi*effect)/2.0)*offpe
```

```
                endif
              elseif (mct.lt.4) then
                write(*,800)id,lat,nct,mct
800             format(1x,i6,1x,f5.2,2(1x,i2))
                effect=(oldeff(ict-2)+oldeff(ict-1))/2.0
                oldeff(ict)=effect
                oldso(ict)=so(m)
                if (effect.ge.0.6366197) then
                  pengs=offpe
                else
                  pengs=sqrt((pi*effect)/2.0)*offpe
                endif
                nct=0
                mct=mct+1
              else
                write(*,800)id,lat,nct,mct
                sumso=0.0
                sumeff=0.0
                do jct=1,100
                  sumso=sumso+oldso(jct)
                  sumeff=sumeff+oldeff(jct)
                enddo
                so(m)=sumso/100.0
                eff(m)=sumeff/100.0
                done=.true.
              endif
            endif
          enddo
        enddo
        write(15,950)lat,so(2),so(3)
950     format(3(1x,f8.3))
        write(16,975)staid,so(2),so(3),(factor(j),j=1,4)
975     format(1x,i6,6(1x,f4.2))
      endif
1000  return
      end
```

```
c       SMANDNPP.FOR
c       to compute npp adjusted for soil moisture deficits
c       revised 5/1/89 to include all changes to date
c
        integer state,id,type,maxt(365),mint(365),avgt(365),
       $error,count,precip(365)
        real cmaxt(365),cmint(365),cavgt(365),spsi(6,4)
        open(10,file='climate.dat',status='old')
        open(13,file='stalat.dat',status='old')
        open(15,file='nppso.dat',status='new')
        open(16,file='soinput.dat',status='old')
        open(17,file='slin.dat',status='old')
c
c       read in climate normals
c
        count=0
          do k=1,6
            read(17,*)(spsi(k,m),m=1,4)
          enddo
        do i=1,167
          read(10,50)state,id,type,(maxt(j),j=1,365)
          count=count+1
          read(10,50)state,id,type,(mint(j),j=1,365)
          read(10,50)state,id,type,(avgt(j),j=1,365)
          read(10,50)state,id,type,(precip(j),j=1,365)
50        format(1x,i2,i4,i1,365i3)
          do j=1,365
            cmaxt(j)=float(maxt(j)—32)*(5./9.)
            cmint(j)=float(mint(j)—32)*(5./9.)
            cavgt(j)=float(avgt(j)—32)*(5./9.)
          enddo
          write(*,70)state,id
70        format(' calling mainprog, id no: ',i2,i4)
          call mainprog(cmaxt,cmint,cavgt,state,id,error,
       $       count,precip,spsi)
          if(error.eq.1) goto 500
        enddo
500     stop
        end


        subroutine mainprog(cmaxt,cmint,cavgt,state,id,error,
       $count,precip,spsi)

        integer staid,state,gsnet(3),type,gs,dd,df(3),ds(3),
       $error,count,precip(365),count2,gsnot,npp(3)
        real newavg(365),lat,lai(3),laiful(3),newmax(365)
       $,newmin(365),kv(3),et(3),totet(3),c(3),spsi(6,4),
       $kterm
        dimension cmaxt(365),cmint(365),cavgt(365),w(3),
       $factor(4),so(3),prevso(3)
```

```
      logical done
      data laiful/1.0,1.0,1.0/
      data kv/0.36,0.66,0.31/
      alpha=.003
      staid=(state*10000)+id
      error=0
      read(13,*)idsta,lat1,lat2
      if(idsta.ne.staid) then
        write(*,100)staid,idsta
100     format(1x,'error in id weather data= ',i5,' and npp data= ',i5)
        error=1
        goto 1000
      endif
      lat=float(lat1)+(float(lat2)/60.)
      if (lat.lt.38.0) then
        read(16,*)idsta,so(2),so(3),(factor(j),j=1,4)
        zr=172.44–(3.3609*lat)
        psec=5.0
        cond=(30.77–0.78*lat)*24.0
        poros=0.4
        kterm=cond/(zr*poros)
        do i=1,365
          newmax(i)=cmaxt(i)
          newmin(i)=cmint(i)
          newavg(i)=cavgt(i)
        enddo
        gs=0
        totpr=0
        do k=1,3
          gsnet(k)=0
          totet(k)=0
          ds(k)=0
          df(k)=0
          prevso(k)=so(k)
          w(k)=1.0
        enddo
        dd=0
        totpe=0
        do i=1,365
          totpr=totpr+(float(precip(i))/100.0)
          call getpe(i,lat,newavg(i),daype)
          do type=2,3
            l1=(2*type)–3
            pterm=(float(precip(i))*factor(l1))/(100.*zr*poros)
            if (type.eq.3) then
              lai(type)=laiful(type)
              call getc(type,newmax(i),newmin(i),newavg(i),c(type))
              if(c(type).ne.0) df(type)=df(type)+1
            else
              c(type)=1.0
              call getlai(gs,dd,lat,newavg(i),pct,i,df(type),ds(type))
```

```
              lai(type)=laiful(2)*pct
            endif
            et(type)=daype*c(type)*lai(type)*w(type)
            eterm=(et(type)*kv(type))/(zr*poros)
            totet(type)=totet(type)+et(type)
            if((gs.eq.1).or.(type.eq.3)) then
              done=.false.
              do while (.not.done)
                compso=so(type)
                sterm=((prevso(type)+so(type))/2.)**psec
                so(type)=prevso(type)+pterm—eterm—
     $            kterm*sterm
                if (so(type).gt.1.0) so(type)=1.0
                tol=abs(compso—so(type))
                if(tol.le..001) then
                  done=.true.
                  prevso(type)=so(type)
                endif
              enddo
              conda=cond/24.0
              if(conda.ge.8.3) then
                condb=8.3
                n1=1
                n2=2
                cdiv=3.75
              elseif(conda.ge.2.41) then
                condb=2.41
                n1=2
                n2=3
                cdiv=5.89
              else
                condb=1.02
                n1=3
                n2=4
                cdiv=1.39
              endif
              if(so(type).gt.spsi(3,n2)) then
                w(type)=1.0
              else
                call getw(spsi,so(type),n1,n2,cdiv,w(type),
     $            conda,condb)
              endif
            endif
          enddo
          totpe=daype+totpe
        enddo
        do m=2,3
          npp(m)=nint(kv(m)*alpha*25400*totet(m))
        enddo
        write(15,950)lat,npp(2),npp(3)
950     format(1x,f5.2,2(1x,i6))
```

```
      endif
1000  return
      end

      subroutine getw(spsi,so,n1,n2,cdiv,w,cond,condb)
      dimension spsi(6,4)
      if(so.lt.spsi(6,n1)) then
        barsa=15.0
      elseif(so.lt.spsi(5,n1)) then
        difft=spsi(5,n1)-spsi(6,n1)
        diffb=5.0
        diffs=spsi(5,n1)-so
        barsa=10.0+5.*(diffs/difft)
      elseif(so.lt.spsi(4,n1)) then
        difft=spsi(4,n1)-spsi(5,n1)
        diffb=3.
        diffs=spsi(4,n1)-so
        barsa=7.+3.*(diffs/difft)
      elseif(so.lt.spsi(3,n1)) then
        difft=spsi(3,n1)-spsi(4,n1)
        diffb=3.
        diffs=spsi(3,n1)-so
        barsa=4.+3.*(diffs/difft)
      elseif(so.lt.spsi(2,n1)) then
        difft=spsi(2,n1)-spsi(3,n1)
        diffb=2.
        diffs=spsi(2,n1)-so
        barsa=2.+2.*(diffs/difft)
      elseif(so.lt.spsi(1,n1)) then
        difft=spsi(1,n1)-spsi(2,n1)
        diffb=1.
        diffs=spsi(1,n1)-so
        barsa=1.+(diffs/difft)
      else
        barsa=1.0
      endif
      if(so.lt.spsi(6,n2)) then
        barsb=15.0
      elseif(so.lt.spsi(5,n2)) then
        difft=spsi(5,n2)-spsi(6,n2)
        diffb=5.0
        diffs=spsi(5,n2)-so
        barsb=10.0+5.*(diffs/difft)
      elseif(so.lt.spsi(4,n2)) then
        difft=spsi(4,n2)-spsi(5,n2)
        diffb=3.
        diffs=spsi(4,n2)-so
        barsb=7.+3.*(diffs/difft)
      elseif(so.lt.spsi(3,n2)) then
        difft=spsi(3,n2)-spsi(4,n2)
        diffb=3.
```

```
  diffs=spsi(3,n2)—so
  barsb=4.+3.*(diffs/difft)
elseif(so.lt.spsi(2,n2)) then
  difft=spsi(2,n2)—spsi(3,n2)
  diffb=2.
  diffs=spsi(2,n2)—so
  barsb=2.+2.*(diffs/difft)
elseif(so.lt.spsi(1,n2)) then
  difft=spsi(1,n2)—spsi(2,n2)
  diffb=1.
  diffs=spsi(1,n2)—so
  barsb=1.+(diffs/difft)
else
  barsb=1.0
endif
diffc=cond—condb
pct=diffc/cdiv
delbar=(barsa—barsb)*pct
bars=barsb+delbar
if (bars.le.4.4) then
  w=1.0
elseif (bars.ge.14.1) then
  w=0.0
else
  w=1.454—.1031*bars
endif
return
end
```

Appendix C (continued)

Common Subroutines

```
      subroutine daylen(jul,lat,day2)
      real lat
      pi=3.1415926535
      phi=lat*(pi/180.0)
      delta=0.4093*cos(0.0172*(172.-float(jul)))
      dayrad=-1.0*tan(delta)*tan(phi)
c     correction for white nights and dark noons
      if (abs(dayrad).gt.1.0) dayrad=dayrad/abs(dayrad)
      sunset=12.0+((24.0/(2.0*pi))*acos(dayrad))
      sunrise=12.0-((24.0/(2.0*pi))*acos(dayrad))
      day=sunset-sunrise
      day2=(day/12.0)**2
c     write (*,1200)jul,day
1200  format(1x,'computing daylength...on day ',i3,' equal to ',f10.4)
      return
      end

      subroutine getc(type,max,min,avg,c)
      real max,min,avg,c
      integer type
      if((max.lt.0).and.(min.lt.0)) then
        c=0.0
      else
        if(type.eq.1) then
          if(avg.le.-6.0) then
            c=0.0
          elseif(avg.lt.0.0) then
            c=1.0+(avg/6.0)
          elseif(avg.le.20.0) then
            c=1.0
          else
            c=1.0-((avg-20.0)/15.0)
          endif
        else
          if(avg.le.0.0) then
            c=0.0
          elseif(avg.lt.10.0) then
            c=avg/10.0
          else
            c=1.0
          endif
        endif
      endif
      return
      end
```

```
subroutine getlai(gs,dd,lat,temp,pct,jul,df,ds)
integer gs,dd,jul,df,ds,degday,elapsed,color
real lat,temp,pct
color=nint(392.0—(2.8*lat))
if (jul.lt.32) then
  pct=0
else
  if(gs.eq.0) then
    if(df.eq.0) then
      if(temp.gt.5.0) then
        degday=nint(temp—5.0)
        dd=dd+degday
        if(dd.ge.194) then
          gs=1
          ds=jul
        endif
      endif
    endif
    pct=0
  else
    if(df.eq.0) then
      elapsed=jul—ds
      if(elapsed.le.19) then
        pct=tanh(0.17*float(elapsed))
      else
        pct=1.0
        if(jul.eq.color) then
          df=jul
        endif
      endif
    else
      elapsed=jul—color
      pct=1.0—(0.0588*float(elapsed))
      if(elapsed.eq.17) then
        gs=0
      endif
    endif
  endif
endif
return
end
```

```
subroutine getpe(day,lat,temp,daype)
integer day
real lat
call daylen(day,lat,day2)
call getrho(temp,rho)
factor=0.9237+0.0086*lat
daype=0.55*day2*rho*factor
return
end

subroutine getrho(temp,rho)
abst=temp+273.15
satpres=2.5605e9*exp(-5423.0/abst)
rho=(0.622*satpres*1.0e7)/(2.876e6*abst)
return
end
```