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Productivity of boreal forests in relation to climate and vegetation zones

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Many properties of forest stands in the boreal main zone have means that are specific to each boreal zone (i.e. subzones of the main climatic zone). These properties are arranged in zonal systems, called forest vegetational zones. The paper examines the vegetative productivity using three climatic variables: the effective temperature sum, the duration of the vegetation period, and the maximum soil frost penetration; each of them means for the period 1961–2000. Soil frost penetration was calculated mainly as a function of snow depth and frost sum. The productivity for each boundary between the boreal forest vegetational zones in Finland was obtained mainly from Ilvessalo, beginning with the boundary between the hemiboreal and southern boreal zones in the south and ending at the boundary between the middle and northern boreal zones in the north. The regional distribution of residuals reflects the regional variation of the soil fertility. A hypothesis that each boundary corresponds to a certain productivity from the western coast of Norway to western Siberia, was tested. The productivity for the boundary between the hemiboreal and temperate zones was found to be in accordance for the limit determined by vegetation. Some applications of the results are presented.

Introduction

In the boreal zone, forests and mires cover most of the ground surface. The structure of growing stands is a key factor affecting the energy and water balance of the ground surface, the diurnal temperature variation and the depth and steepness of the surface inversion. Conversely, the main climatic variables, the duration of the vegetation period, the effective temperature sum, and the depth of soil frost (which, in turn, is mainly determined by the mean snow depth and frost sum in winter) are the main factors that determine the forest vegetation, forest productivity and occurrence of peatlands. The boreal vegetation and climate form regional systems of mutual interaction that are circumpolar and separated from each other by transition zones that are characterised by steep gradients in biological and climatic variables. These systems, called boreal ecoclimatic zones, are shown in Fig. 1 for northern Europe (Tuhkanen 1984). To delineate these zones, soil frost maps for forests and open fields were prepared on the basis of soil frost and snow depth observations and frost sums. The main purpose of this study is, first, to obtain the productivity of the boreal nature as a function of climatic variables, not only considering the vegetation period, but also winter, by considering the effect of soil frost. A preliminary attempt was made by Solantie (2003) who has found that the spatial distribution of the growth of forests in the

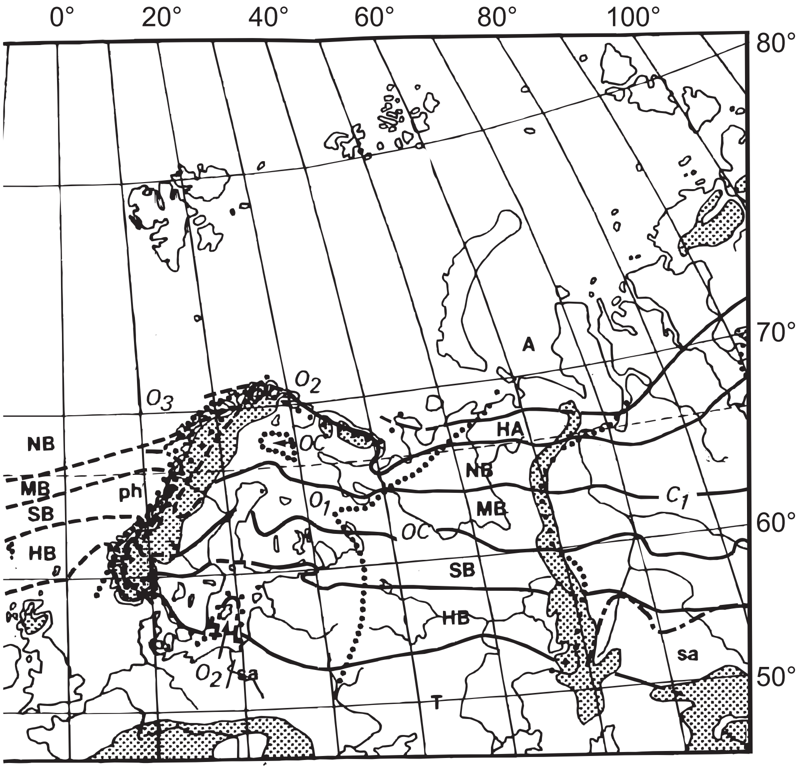

Fig. 1. The boreal and neighbouring zones in Europe after Tuhkanen (1984). Here T is the temperate zone (next south of the boreal main zone), HB is the hemiboreal zone, SB is the southern boreal zone, MB is the middle boreal zone, NB is the northern boreal zone, HA is the hemiarctic zone (transformation towards the arctic) and A is the arctic zone.

southern half of Finland could not be explained by climatic variables concerning the vegetation period alone (e.g. Karlsson 1996). The second aim of the paper is to test the hypotheses that the boreal subzones of the main boreal zone form both vegetational and climatic systems and that these zones are characterized by uniform productivities.

Productivity is connected to many climatic variables, such as evapotranspiration and minimum temperatures in inversion situations. The relation of productivity to minimum temperatures is caused by the dependence of the mean height of tree stands on the productivity. The mean height of tree stands is equal to the height of the main radiating surface and the thickness of the layer beneath the crown level, both crucial for the steepness of inversion and minimum temperatures.

This report is aimed at foresters, climatologists and biologists to help them understand the mutual interaction and relationships between the two major components of boreal nature. This report also is meant to outline the need for further research in this field.

Methods

Calculation and mapping of the greatest soil frost depth

Basic equation for soil frost

Equations for soil frost were adjusted for open fields and forests following the method of Andersson (1964) for Swedish conditions and applied by Solantie (2000). In the latter study, soil frost observations for all kinds of soils were employed, while in the present study coarse soils of uniform particle size, occurring mostly in glacial eskers, have been excluded from the basic material because of particular soil frost conditions in such soils. Adjustments to the values of constants in the formulae were also made. The results are consequently more accurate but they are restricted to the soils other than coarse sands and gravels.

According to Andersson, the soil frost depth F (cm) at t days after the onset of freezing can be given as:

$$F = [2cP + (bD_{mean})^2]^{0.5} - bD_{mean} - 0.5cat \quad (1)$$

where P (–°C d) and D_{mean} (cm) are the frost sum and mean snow depth, respectively, during the period t (days) and a is the temperature gradient in soil beneath the soil frost (°C cm^{-1}). The coefficients b and c are given by $b = k_1/k_2$ and $c = c_m k_1/(C_M\, w)$ (cm^2 d^{-1} °C^{-1}), where k_1 is the heat conductivity of frozen soil (J cm^{-1} s^{-1} °C^{-1}), k_2 is the heat conductivity of snow (J cm^{-1} s^{-1} °C^{-1}), c_m is a coefficient giving the number of seconds in 24 hours (= 86 400), C_M is the freezing heat of water (J g^{-1}), and w is the volumetric proportion of water in freezing soil.

The last term of Eq. 1, $-0.5cat$, denoted by H, gives the retardation of the deepening of soil frost due to heat rising from below the frozen soil layer. In this study particularly, F represents the winter's maximum soil frost depth, averaged over the period 1961–2000, while t is the period from the onset of soil frost up to 31 March as soil frost is generally about at its maximum. The mean temperature corresponding to the date of the onset of soil frost is about –3 °C but varies spatially somewhat according to the amount of snowfall. In Finland, the map of the date by Huttunen and Soveri (1993) was available.

Equation for open fields

For open fields, we have $k_1 = 0.019$, $w \approx 0.3$ and $C_M = 335$ in Eq. 1, so that $c = 16.4$. Furthermore, $P = pP_o$, where P is the average frost sum at the snow surface, P_o is frost sum at the 2-m level and p is a calibration coefficient set at 1.05. According to Andersson (1964), b lies in the range 2–23. By taking into account that high values of b apply to fresh fallen snow but not to old snow lying on the ground, and by noting that the heat conductivity of snow cover increases with temperature and the occurrence of thaws, the value of b is set so that it increases from 4 in southwestern Finland to 12 in Lapland. Approximating $b = 0.063 \times P^{0.7}$, which means that db/dP is inversely proportional to $P^{0.3}$, so we have $b = 4$ for $P = 377$, $b = 6$ for $P = 673$; $b = 8$ for $P = 1016$, $b = 10$ for $P = 1398$, and $b = 12$ for 1814. The climatic mean, D_{mean} can be approximated as the mean snow depth on 15 January plus 2 cm.

Let us approximate the last term of Eq. 1, H, giving the retardation of the deepening of soil frost due to heat rising from below the frozen soil layer. According to soil temperature observations at 20 and 50 cm by the Finnish Meteorological Institute (FMI), the mean value of at for 1971–1990 at stations south of the Arctic Circle was 4.03 (Heikinheimo and Fougstedt 1992) and the value of the last term of Eq. 1 was –36.5 cm. When using 50 and 100 cm temperatures, the last term becomes –32.5 cm. The mean value of the Finnish soil temperature stations was therefore taken as –34.5 cm. This term is approximately proportional to the effective temperature sum of the previous summer (L). Given that at the soil temperature stations on average $L = 1150$ (°C d), we have:

$$H\,(\mathrm{cm}) \approx -0.027 \quad (2)$$

after which Eq. 1 becomes:

$$F = \{34P_o + [0.063D_{mean}(1.05P_o)^{0.7}]^2\}^{0.5} - 0.063D_{mean}(1.05P_o)^{0.7} - 0.027L. \quad (3)$$

Equation for forests

The following values are employed in Eq. 1 to obtain F for forests: $k_1 = 0.021$ (slightly higher than on fields, less organic material), $w \approx 0.3$ and $C_M = 335$, so that $c = 18.1$. Similar to previous subsection, $P = pP_o$ where P is the average frost sum at the snow surface, P_o is frost sum at the 2-m level and p is calibration coefficient set at 1.05.

In the forests, the heat conductivity of snow increases less with temperature and occurrence of thaws than on fields because the shrub vegetation under the snow creates insulating air pockets between ground and snow. This effect increases the more the snow contains refrozen ice particles and the greater the pressure of the snow cover. Therefore, for the forests b varies less geographically than for open places. It cannot be very small in southwestern Finland. Approximating db/dP to be inversely proportional to P, and setting b as $b = 1.4\ln P$, we have $b = 8.5$ for $P = 433$, $b = 9$ for $P = 619$; $b = 9.5$ for $P = 885$, and $b = 10$ for $P = 1265$, and $b = 10.5$ for 1808. The climatic mean D_{mean} can be approximated as the mean snow depth on 15 January plus 2 cm.

The last term of Eq. 1 can be written as:

$$H\,(\mathrm{cm}) \approx -0.03L \quad (4)$$

after which Eq. 1 becomes

$$F = \{38P_o + [1.4D_{mean} \times \ln(1.05P_o)]^2\}^{0.5} - 1.4D_{mean} \times \ln(1.05P_o) - 0.03L. \quad (5)$$

An alternative to Eq. 5 that produces practically equal results is an equation where the term $1.4D_{mean} \times \ln(1.05P_o)$ is replaced by the term $(2.5D_{mean}(1.05\ P_o))^{0.2}$, according to which F in forests is proportional to the frost sum to the power of 0.2, while on open ground, according to Eq. 3, it is proportional to the frost sum to the power of 0.7.

Note that Eqs. 3 and 5 apply satisfactorily to moraine, silt, clay and even fine sand. These equations cannot be applied to sand or gravel or to soils with rather even-sized particles due to their poor water retention capacity and low values of w in Eq. 1. Consequently, soil frost in these soils is appreciably deeper than in other soils, while the amount of ice in the soil frost layer is less.

To observe the improvement in the accuracy of the results compared to the preliminary ones (Solantie 2000), Eqs. 3 and 5 were applied to the same data as used in the preliminary survey (Huttunen and Soveri 1993, Solantie 2000) for the winters 1968/1969–1989/1990. Some series were not complete, but those including at least 14 winters were accepted. Denoting observed values by F_o, a regression equation for all sites from the 60th to the 66th latitude (fields) and from the 60th to the 69th latitude (forests), excluding sites on coarse sand or gravel, was calculated as

$$F = c_1 + c_2F_o \quad (6)$$

where c_1 and c_2 are constants.

Testing soil frost equations against observations and their use for soil frost maps

To obtain soil frost maps, Eqs. 3 and 5 were applied to the gridded values of frost sum and snow depth for the period 1963–1998 (Solantie 2000). The values of snow depth and frost sum for this period are practically the same as those for the period 1961–2000. Further, snow depths for this period are, in all parts of Finland, very close to those for the period 1919–1998 as a whole (Solantie 2000). The mean values of D during the period of soil frost were approximated by adding 2 cm to the snow depths on 15 January. Gridded maps of the snow depth on 15 January for the period were available for the total land area only; only for the period 1947–1963 values both for forests and open places were available. For the other periods, values for forests and open places and forests were obtained introducing their differences as they were 1947–1963. Concerning the mean winter temperature and frost sum, the values for the periods 1961–2000, 1919–1998, and 1971–1990 (soil frost observation period) are about equal, while the period 1961–1990 is colder and 1971–2000 milder than the first three periods (e.g. Tuomenvirta and Heino 1996, Tuomenvirta *et al.* 2000).

Productivity and volume of growing stands

The area of poorly productive and waste lands in Finland is currently smaller than in earlier periods due to the drainage of mires to increase the volume, height and growth of trees. During the past 40 years, the values of these forestry variables have been lower than in previous periods because of large-scale logging.

In the 1950s, the volume of growing stands in the southern half of Finland was rather low due to the unsustainable use of forests during the preceding 50 years, and the annual growth was less than the productivity (Ilvessalo 1961). During the past 20 years, the volume of growing stands has been appreciably higher and growth has been approximately at the level of productivity (e.g. Tomppo 2000). The age structure of forests in the southern and middle boreal zones are the same. The age classes (in years) of below 40, 40 to 80 and over 80 each comprised 1/3 of the forests. This was not the case in the 1970s, when the middle age class comprised 43% of forests in the southern boreal (SB) and 27% in the middle boreal (MB) zones (Yearbooks of forest statistics 1977–1978, 1993–1994). Consequently, the volume of the growing stock in the national forest inventory carried out during the period 1983–1993 (Yearbook of forest statistics 1993–1994) can be satisfactorily related to productivity (Ilvessalo 1960).

Forest productivity as function of climate

The basic equation for the coefficient of the biospheric productivity (B) in the boreal system can be given as a sum of two components as

$$B = B_a + B_b \tag{7}$$

where B_a determines ecological conditions above the ground (assimilation) and B_b below it (root system, decomposition). B should be approximately constant at each boundary between the zones. We may approximate B_a as

$$B_a \approx g + lL \tag{8}$$

where g and l are constants and L (°C d) is the effective temperature sum above +5 °C.

Because the decomposition of organic matter also occurs outside of the vegetational period, and because the initiation of growth of deep-rooted vegetation such as trees is delayed by soil frost, the temperature sum between 0 and 5 °C and the soil frost depth are important. Consequently, variable B_b can be approximated as

$$B_b \approx l_b L_b + fF \tag{9}$$

where l_b is a positive constant, L_b is the temperature sum between 0 and 5 °C, f is a negative constant and F is the winter's maximum soil frost depth (cm). Further note that

$$L_b = 5V + L_{sp} + L_{au} \text{ (°C d)} \tag{10}$$

where V is the duration of the vegetational period (d) and L_{sp} and L_{au} are parts of L_b gathered between 0 and 5 °C in spring and autumn, respectively, being the greater, the slower the mean temperature changes in spring and autumn. The value of L_b was roughly approximated as 5.6V. By considering this approximation and combining Eqs. 7–9, we obtain:

$$B = g + lL + vV + fF \tag{11}$$

where v is a constant.

Equation 11 is called the basic equation for boreal nature. The main goal of this study is to estimate the values of the coefficients of this equation. Tuhkanen (1984) used biotemperature B_0, i.e. the annual sum of daily mean temperatures divided by 365, for the purpose of Eq. 11. So, in this article, the weighted mean of V and L is used instead of B_0. The use of B_0 means that each degree of daily mean temperature above the freezing point in April during snow cover, or in November with minimal solar radiation, has a biological effect that is equal to that in summer while the weighted mean of L and V sets more weight for the considered parameter in summer. So, coefficients produced separately both for L and V by regression analysis may increase the accuracy of the results.

Equation 11 was solved by a linear regression analysis on the basis of observations in Finland. B was approximated by the productivity of productive forests in terms of solid wood material without bark, denoted by G (m^3 ha^{-1} a^{-1}). The productivity was explained by a regression equation as a linear function of the effective temperature sum, denoted by L (°C d) and winter's maximum soil frost depth, denoted by F (cm):

$$G = g + lL + vV + fF \tag{12}$$

Consider that for each isoline of L in northern Europe, V increases from Siberia to the western coast of the continent. If applied to a country like Finland with a small west–east extension, Eq. 12 can be simplified to

$$G = g_0 + l_0 L + f_0 F \tag{13}$$

where g_0, l_0, and f_0 denote values of the constants g, l and f in the simplified version. The regression analysis was made also using this simpler version.

A regression model similar to Eq. 13 was presented by Solantie (2000). In the present study, more precise values of F for the period

1961–2000 have been used. The productivity of forests is a rather stable variable, depending somewhat upon earlier climatic periods. Therefore, values of F and L should be averages over rather long periods. The basic material was for 40 km-side grid squares, covering Finland south of the Arctic Circle. The area therefore includes all boreal zones from hemiboreal to northern boreal. Values of G were obtained from Ilvessalo (1960). Considering values of L, those for the period 1931–1960 are, all over northern Europe, only about 15 °C d (1% to 1.5%) higher while those for the period 1961–1990 are 15 °C d lower than those for the period 1961–2000 (e.g. Tuomenvirta 2004). So, grid values of $L_{1961–2000}$ used in Eq. 13 were obtained by subtracting 15 °C d from those for the period 1931–1960.

The boreal zones and their climatic definition

Boreal zones as forest vegetational units

The boundaries between the temperate and hemiboreal (T/HB), the hemiboreal and southern boreal (HB/SB), the southern and middle boreal (SB/MB), and the middle and northern boreal (MB/NB) have been determined by botanists, first by Kalela (1961) for Finland, and then by Sjörs (1967), Ahti *et al*. (1968) and Tuhkanen (1984) (Fig. 1). Climate was taken into account on the basis of the period with mean temperatures above freezing point. Soil frost was not considered. Tuhkanen (1984) uses constant values for the biotemperature, i.e. the annual sum of daily positive mean temperatures (°C d) divided by 365, as a climatic control for the forest vegetational boundaries. This variable is better than V or L alone, and in skill roughly comparable to the weighted mean of L and V. At the western end of the boundary between the southern and middle boreal zones in Finland, the value of biotemperature is 56 while at the eastern end the value is 51. The difference can be explained by the appreciable difference of 16 cm in F. Consequently, in this article, the boundaries are defined as equations of climatic variables, taking soil frost into account, and adjusting the coefficients to produce boundary lines that lie in the middle of the three versions of this boundary as determined by botanists.

In Finland, there is both climatic and vegetational evidence of steep gradients across the boundary between the southern and middle boreal ecoclimatic zones. For example, the volume of growing stands in forests, including both good and poorly productive forests, decreased by 30 m^3 ha^{-1} per 25 km, from 115 m^3 ha^{-1} in the SB to 85 m^3 ha^{-1} in the MB across and along this boundary (Tomppo 2000). Karlsson (1996) also noted a particularly steep gradient in the dominant height of forest stands across the boundary belt. The proportion of grass herb and similar forest types of the forest area also decreases from above 20% in the SB to below 5% in the MB across the boundary (Tomppo 2000). Further, many common plant species and their groups show a distinct gradient at the boundary between the southern and middle boreal zones. Some species, for example *Vaccinium uliginosum*, *Andromeda polifolia*, *Betula nana*, *Spaghnum recurvum coll*., *Ledum palustre*, and *Empetrum nigrum* are more common in the MB than in the SB; the latter species increases still further from MB to NB. These species are typically mosses and dwarf shrubs. On the other hand, some species, for example *Maianthemum bifolium*, *Oxalis acetosella*, *Convallaria majalis*, *Viola riviniana*, and *Carex digitata* are more common in the SB. Of these species, all except the last one, are grasses. For *Carex digitata*, soil nutrients seem to be important because the maxima of the coverage seem to be located in grass–herb centres (Etelä-Suomen metsien suojelutarvetyöryhmä 2000). For maps of distributions *see* Vanha-Majanmaa and Reinikainen (2000), Hotanen (2000), Reinikainen (2000), Tonteri (2000), and Silferberg (2000).

The climatic definition of the boundaries between the boreal zones

The determination of the forest vegetational zones as a function of climatic variables is based on the hypothesis that variable B in Eq. 12 and the productivity G in Eq. 13 should be constant along the boundary, while g, l, v, and f have constant values all over the boreal zone. The values of these constants were obtained by applying Eq. 12 to the boundaries in question in Finland.

Substituting values of G in Eq. 6 with solved coefficients, the locations of the boundaries at a sample of latitudes from the western coast of Norway to western Siberia could be found as a function of climatic variables L, V and F. The longitudes chosen (°E) were 6, 13, 22, 28, 40, 50, and 70°E. The location of the boundary between the hemiboreal and temperate zones was also determined by applying the estimated relation G/K to the observed mean value of K along this boundary (European Forest Institute 2004). Further, locations of two points, one in western Siberia and one in northern Fennoscandia, at which $G = 0$, were determined and compared with the location of the boundary between the northern boreal and hemiarctic zones at the longitudes in question. Finally, the climatic- and vegetation-based locations of the zone boundaries were compared.

Calculation of the productivity and volume of growing stands for the boreal zones and their boundaries

The means of productivity (G) and volume of growing stands in the forests (K) were calculated for zones and their boundaries. The values of G in Finland were calculated from the grid values based on Ilvessalo (1961). The Finnish values of K are calculated from the basic data from the national forest inventory 1984–1987 (Yearbook of Forest Statistics 1993–1994), and Tomppo (2000). The boundary belt between the hemiboreal and southern boreal zones was a particular case. This boundary runs along the northern coast of the Gulf of Finland where barren and stony rapakivi granites and bare rocks reduce productivity. The value of G for this boundary was therefore taken as a mean of the predicted values in Eq. 19. The value of K for this boundary was taken as an average along the boundary from Sweden to the Urals (European Forest Institute 2004). The value of K for the boundary between the hemiboreal and temperate zones was obtained with the same method. For the latter boundary, the relative productivity G/K was obtained by extrapolation (Table 1), and then the value of G was calculated as K (G/K).

Obtaining climatic variables for the productivity for boreal zones

In order to determine the location of a specific boundary at a given longitude, the maximum soil frost depth F around the intersection of the boundary and the considered longitude under consideration was obtained. Values for F were calculated from Eq. 5. For the former Soviet Union, snow depth values and frost sums were based on maps in the World Atlas of Snow and Ice Resources (Russian Academy of Sciences 1997). The maximum water equivalent of the snow cover was first converted into the values of 15 March by a reduction of 15 mm (~10%). Snow depths on 15 March were then obtained by using mean density of snow cover as 0.19 to 0.23 g cm^{-3}, increasing with decreasing frost sum. The mean snow depth for the soil frost period was obtained by multiplying the snow depth on 15 March by 0.7 and finally adding 2 cm. In Sweden, long snow depth time-series were available from the Swedish Meteorological and Hydrological Institute. Values for the soil frost period were approximated using figures for 15 January and adding 2 cm. Values of P in Russia were estimated from an isopleth map, while all the other values of P, V, and L were based on temperature observations at stations.

Table 1. A guidance classification of the main nutrients content of soil as partial dissolution to aqua regia. Indications of rich and poor moraines in the four main nutrients.

Poor moraines	Rich moraines
Ca: partial leach < 0.10%	Ca: partial leach > 0.25%
K: partial leach < 0.07%	K: partial leach > 0.50%
Mn: partial dissolution < 110 ppm	Mn: partial dissolution > 230 ppm
Mg: partial leach < 0.30%	Mg: partial leach > 0.60%

In Sweden values were available for the period 1961–1990 (Alexandersson *et al.* 1991) and for 1931–1960 in Norway and Russia (Bruun 1967, WMO 1971). In the case of Norway and Russia, the same period and station net was employed as used by Tuhkanen (1984) for calculation of biotemperature. The values of L for the periods 1931–1960 and 1961–1990 were then adjusted to the period 1961–2000. Values for the period 1931–1960 all over northern Europe are only about 15 °C d (1% to 1.5%) higher and those for the period 1961–1990 15 °C d lower than those for the period 1961–2000 (e.g. Tuomenvirta and Heino 1996, Tuomenvirta *et al.* 2000). A systematical reduction of L from either of the 30-year periods by 15 °C d was considered to be accurate enough. Correspondingly, values of F for the period 1961–2000 were obtained by adding 5% to the values for the period 1931–1960 and subtracting 5% from the values for the period 1961–1990.

With values for F and G at a given boundary and longitude entered into Eq. 12, and knowing the relation V/L in the region in question, the values of L and V could be solved. The accurate location of the boundary was then obtained by interpolating between observed values of V and L on both sides of the considered boundary. The effect of height above sea level h (m) on the mean temperature T (°C) was taken into account by

$$T(h_2) = T(h_1) - 0.0055\,(h_2 - h_1) \qquad (14)$$

on the duration of the vegetation period V (d) by

$$V(h_2) = V(h_1) + [T(h_2) - T(h_1)][1/(\delta T/\delta t_{sp}) + 1\,(-\,\delta T/\delta t_{au})]\ (\mathrm{d\ m^{-1}}) \qquad (15)$$

and on the effective temperature sum L (°C d) by

$$L(h_2) = L(h_1) + 0.5[T(h_2) - T(h_1)][V(h_1) + V(h_2)]. \qquad (16)$$

Here, –0.0055 is the change of T when ascending one meter (Machenbauer *et al.* 1998), (h_1) and (h_2) denote values at heights h_1 and h_2; $\delta T/\delta t_{sp}$ is the average time derivate of the mean temperature at the beginning of the vegetational period (°C $\mathrm{d^{-1}}$) and $\delta T/\delta t_{au}$ that at the end of it.

The depth of soil frost (F) along the interpolation line was obtained as the function of the snow depth (D) and frost sum (P) during the soil frost period. Finally, these climate-based locations were compared with the locations of the corresponding vegetational boundaries at these longitudes.

Some applications

Figures for the evapotranspiration in the forests (E_f) has been obtained for various drainage basins mainly on the basis of the water balance equation by Hyvärinen *et al.* (1995). Guidance values of E_f were obtained as a function of climatic variables, by explaining E_f as a function of G, and substituting G as a function of climatic variables, as given in Eq. 13.

The role of soil frost in determining the regional distribution and temporal variation of some perennials in the lower vegetation strata is even larger than for forest trees, although it is generally overlooked. Damage to perennials was also studied in the light of distribution maps for three periods (Reinikainen *et al.* 2000).

In many applications of climatology and forestry, it is useful to know the approximate magnitude of the partial derivatives of one variable with respect to the other. Derivatives of G with respect to climatic variables could be obtained from Eq. 13, and the others as relations of the differences between the values in the middle and southern boreal zones in Finland. One important partial derivative is that which gives the effect of the height of growing stands on minimum temperature during a surface inversion.

The effect of soil fertility

The accuracy of the estimated forest productivity as a function of climatic variables was determined not only on the basis of the regression analysis but also by comparing the regional distribution of the regression residuals of Eq. 13 with the occurrence of grass–herb centres as recognised by botanists, as well as the distribution of the main nutrients in the soils and rocks. The areas of the grass–herb centres were obtained from the working group on the need for forest protection in southern Finland (Etelä-Suomen metsien suojelutarve-työryhmä 2000). The spatial distributions of the main nutrients (Ca, K, Mg, Mn) in moraine, the most common soil in Finland, and the fertility of rocks (Geological Survey of Finland 1992), were used as indices. In determining the correspondence between vegetation and the general soil classification, the approximate limits of poor and rich nutrient-content were used (Table 1).

Estimation of the accuracy of the climatic definition of the delimitated zones

The use of forest productivity figures to determine the location of the boundaries between the forest vegetational zones as isolines, each with a constant productivity, provides a good test of the accuracy of the basic equation representing boreal nature. If these theoretical locations of the boundaries, each running from the Atlantic coast to western Siberia, are in accordance with the location of the boundaries determined on the basis of the vegetation, such a fit cannot be accidental. The 95% confidence limits of the errors of the locations of the boundaries could be also calculated considering the accuracy of the three climatic variables in Eq. 12. The accuracy of the effective temperature sums depends on the accuracy of the reduction of the data to the period 1961–2000, and the local representativeness of the observed temperatures. The accuracy of the soil frost term depends on the accuracy of frost sum and snow depth. The accuracy of the frost sum is based on the representativeness of temperature observations and the accuracy of the adjustment to the period in question, while the accuracy of snow depth depends mainly on the spatial density of the network of snow observations in relation to actual orographical variations.

Results

Soil frost on open fields

The results from Eq. 3 agree well with the soil frost and snow depth observations by the Finnish Environment Institute. To test the increased accuracy of the results as compared with that of Solantie (2000), Eq. 3 was tested using data of Huttunen and Soveri (1993) for the winters 1968/1969–1989/1990. Some series were not complete but those that included at least 14 winters were accepted. Denoting observed values by F_o, a regression equation for all sites from the 60th to the 66th latitude (excluding those with coarse sand or gravel), the regression equation (17) was obtained with a correlation coefficient of 0.87

$$F = 0.6 + 0.982F_o. \qquad (17)$$

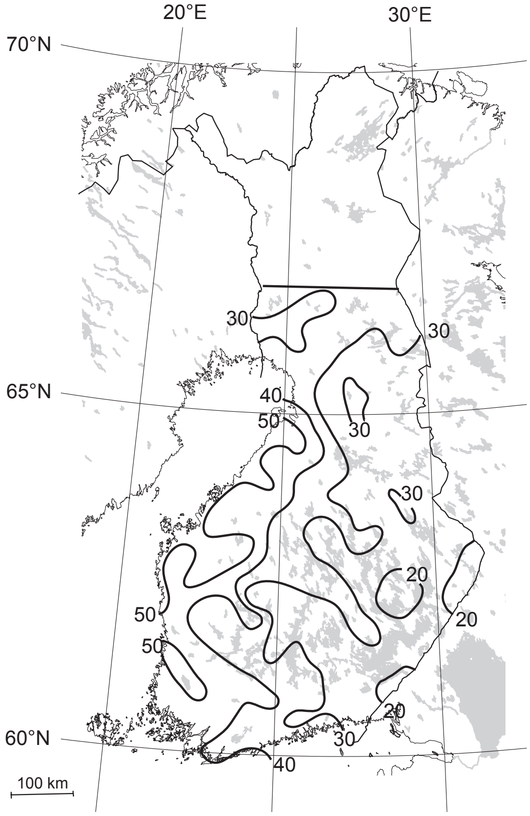

Fig. 2. The greatest soil frost depth (cm) in winter on open places. Average for the period 1961–2000.

Equation 3 can be considered to correspond well to soil frost observations from open places, and the map based on it (Fig. 2) can be considered to be correct.

As result, we have a map of soil frost depth on open fields (Fig. 2) and another for the zone between deep and shallow soil frost on open

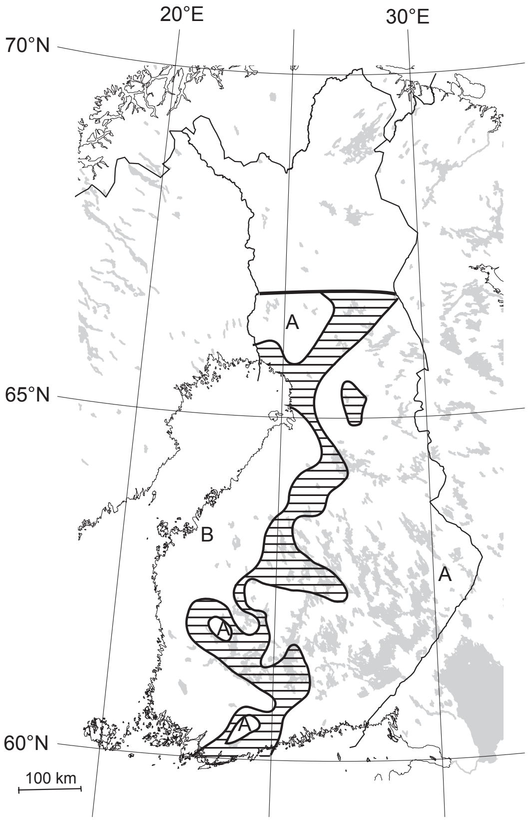

Fig. 3. The zone between deep and shallow soil frost on open fields.

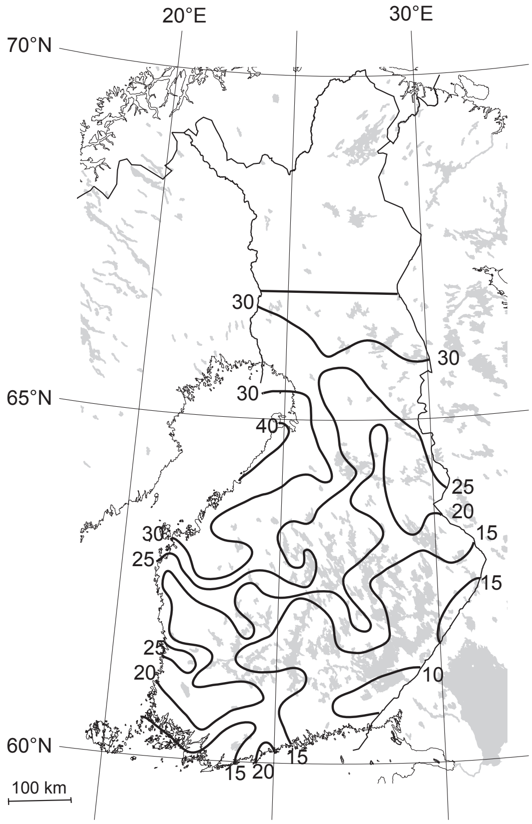

Fig. 4. The greatest soil frost depth (cm) in winter in the forests. Average for the period 1961–2000.

fields (Fig. 3). West of the zone, unfrozen soil and the occurrence of snow mold fungi are rare but east of it they form a significant risk. In the latter area, therefore, the cultivation of Scandinavian winter rye on permanent fields was avoided till the end of the era of traditional agriculture.

The value of F on fields is very sensitive to the changes in D. In the Finnish area south of the Arctic Circle, the climatic mean of D varies from 11 to 51 cm and for F from 17 to 63 cm. Enhancing D by 10%, i.e. 1 to 5 cm, the value of F decreases at all sites by about 10 cm. Such changes are typical when moving from a large field to a small clearing.

Soil frost in forests

The results from Eq. 5 were tested as for Eq. 3. Denoting the observed values by F_o, a regression equation for all sites from the 60th to the 69th latitude (excluding those with coarse sand or gravel) the regression equation (18) was obtained with a correlation coefficient of 0.85

$$F = 1.3 + 0.977F_o. \tag{18}$$

Equation 5 corresponds well with soil frost observations in forests, and the map (Fig. 4) is correct.

The value of F in the forests is less sensitive to changes in D than in the case of fields. For example, suppose average middle Finnish conditions with $P_o = 1000$, $D = 35$ and $L = 1100$, and $F = 21.0$ cm; enhance D by 10% and note that $F = 16.7$ cm; so, $\delta F/\delta D \approx -1.2$.

In the map of soil frost depth (F) in the forests (Fig. 4), F is 15 to 22 cm at the boundary between the southern and middle boreal zones. The bottom of the frozen layer is therefore located at the main layer of tree roots. At the boundary between the middle and northern boreal zones, F is 17 to 32 cm, while at the boundary between the hemiboreal and southern boreal zones $F < 11$ cm.

With respect to the results from the preliminary soil frost survey (Solantie 2000), the most notable amendment is that in the forests of southwestern Finland together with rather mild winters and thin snow cover the soil frost proved to be appreciably thinner than the preliminary result supposes.

Results of the basic equation for forest productivity

The regression analysis explaining G by a linear function of $L_{1961–1990}$, $V_{1961–1990}$, and $F_{1961–2000}$ in Finland south of the Arctic Circle with values for 166 grids results in a basic equation for boreal nature

$$G = -2.50 + 0.00526L_{1961–2000} + 0.0120V_{1961–2000} - 0.0455F_{1961–2000} \quad (19)$$

with correlation coefficient of 0.904 and adjusted R^2 of 0.814. The standard error of the coefficient of F was 0.008, standard error of the coefficient of L was 0.0016, standard error of V was 0.015, standard error of the intercept was 0.86 and the standard error of explanation was 0.55. Replacing V with the annual temperature sum between 0 and 5 °C, the weight of each degree during a single day is about 40% of the weight of each degree above +5 °C during a single day. Temperatures during snow cover (in April) or during low solar radiation (summer nights or late October–early November) are therefore less effective for assimilation and vegetative productivity than during periods with temperatures above +5 °C d.

Neglecting V we obtain Eq. 20

$$G = -1.97 + 0.00647L_{1961–2000} - 0.0435F_{1961–2000} \quad (20)$$

with a correlation coefficient of 0.904 and adjusted R^2 of 0.814. The standard error of the coefficient of F was 0.008, that of the coefficient of L was 0.0004, and that of intercept was 0.59. The standard error of the explanation was 0.55.

Given that the explained variation is the same in both versions, Eqs. 19 and 20 in Finland provide equally satisfactory results. The coefficient of F was also very similar in both versions. Equation 20 is simpler and can be recommended for Finnish applications. Finland has a small West–East extension and so the variation of V in this direction is insignificant. Eq. 19 is more applicable for areas that have a wider West–East extension, particularly for general use when covering the area from the Atlantic coast to Siberia.

According to Eq. 19, the detrimental effect on forest productivity caused by a decrease of 10 days in V can be compensated by increasing L by 23 °C d. Similarly, the detrimental effect on forest productivity caused by an increase of 10 cm in F can be compensated by increasing L by 67 °C d, while according to Eq. 20 the compensation is 87 °C d.

In Eq. 19, the regression residuals explaining G (m^3 ha^{-1} a^{-1}) were from –0.5 to +0.5 for the majority of the area in question (Fig. 5). Considering the regions with greater deviations with respect to vegetational and geological evidence, most of the grids with greater positive deviations correspond to two well-known grass–herb centres of Kuopio and Häme-Satakunta, and the small Uukuniemi grass–herb centre. These areas are also rich in all the nutrients considered here (Geological Survey of Finland 1992; Table 1). Each of these areas is situated in the southern boreal zone; only four such grids occurred in the middle and northern boreal zones south of the Arctic Circle. Only in the Kuopio grid does the residual exceed +1.0. Most of the residuals smaller than –0.5 are concentrated in three regions, each of them having two grids with residuals smaller than –1.0. One of them, located in the southwestern archipelago and coastal areas, consists of bare rocks and rapakivi granites that are poor in all considered nutrients. There are also fertile clayey valleys, most of which are now cultivated. The southeastern negative region corresponds to the southeastern area of rapakivi granites, also poor in all considered nutrients. The northern negative region consists of a plateau north of the 64th latitude. Here, peatlands, half of which were originally fens, cover 60% of the land area, and so the growth of forests was reduced by excess waterlogging. The growth of forests has radically increased after one third of

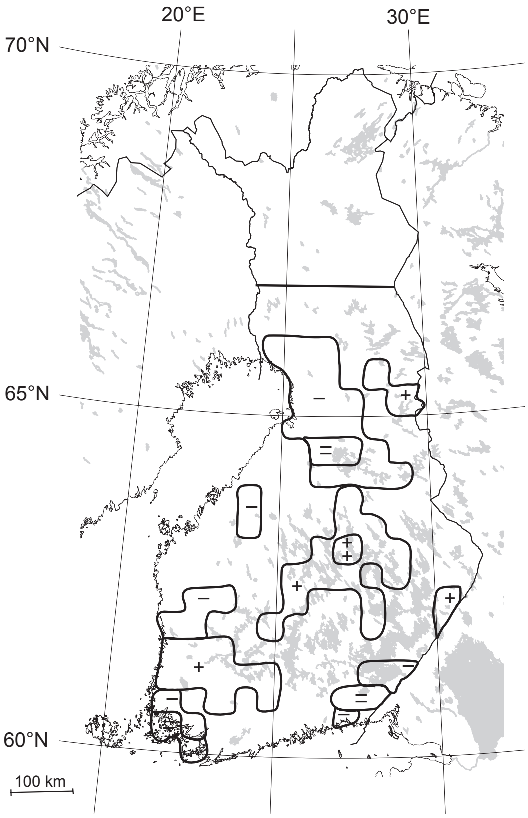

Fig. 5. The residuals of the linear regression analysis (m^3 ha^{-1} a^{-1}), explaining the forest productivity of productive forests by the effective temperature sum and maximum soil frost depth in winter. The residuals are given as < –1.0 (denoted by =), –1.0 to –0.6 (denoted by –), –0.5 to 0.5 (blanco), 0.6 to 1.0 (denoted by +), and > 1.0 (denoted by ++).

the total area of this region was drained during the 1960s, 1970s and 1980s.

The distribution of many demanding plant species, e.g. *Athyrium filix-femina*, reflect the regional distribution of nutrients. The relative area covered by this species increases across and along the boundary between the MB and SB, from below 0.01% to over 0.2% over a distance of 50 km. Within the SB, relative areas over 1% occur in grass–herb centres of Häme, Kuopio and Uukuniemi, while the southwestern and southeastern barren areas stand out with frequencies 0.01% to 0.05% (Nousiainen 2000).

The regional distribution of residuals of the results from Eq. 20 are similar to those for Eq. 19. Only for the smallest of the geologically beneficial areas were the residuals less than +0.5.

Forest productivity and forest vegetational zones

At Salekhardt, which according to Tuhkanen is located in the hemiarctic zone (65.5°N, 65.5°E), $G = -0.5$ m^3 ha^{-1} a^{-1}. The boundary between the hemiarctic and arctic vegetation zones (Fig. 1) is located north of Salekhardt at 67.1°N latitude where $G \approx -1.1$ m^3 ha^{-1} a^{-1}, while the boundary between the northern boreal and hemiarctic forest vegetation zones is situated south of Salekhardt at 65.6°N latitude where $G = 0$. This apparently means that the hemiarctic zone is a region where trees can survive only in places where soil frost is less deep than average. The groups of trees themselves promote their advantageous circumstances by gathering snow as drifts. In Finnish Lapland, the line at which $G = 0$ corresponds to the limit of single pines (e.g. at 67.8°N latitude and 380 m a.s.l.) while the climatic arctic line where $G \approx -1.1$ m^3 ha^{-1} a^{-1} is located at the height of 570 m a.s.l. In the arctic zone, G is negative even for the most favourable sites.

The mean volume of growing stands in the forests K (m^3 ha^{-1}), the mean productivity of the forests (m^3 ha^{-1} a^{-1}), and the relative productivity (G as % of K) are given from north to south for each zone (Table 2). Note that the relative productivity increases southwards by equal zonal steps. Considering that the relative growth of Finnish forests was 3.7% during the period 1951–1953 and 4.0% during the period 1989–1994 (Tomppo 2000), the relative growth seems to be raised by man over the natural productivity by manipulating the age-class distribution. On the other hand, for K and G, the zonal steps are roughly but not exactly even. The reason is that

Table 2. The mean volume of growing stock K (m^3 ha^{-1}), mean productivity G (m^3 ha^{-1} a^{-1}), and the relative productivity (G% of K) in the forests (Fig. 1).

Zone/zone boundary	K	G	$(G/K) \times 100$
NB/MB	57	2.06	3.63
MB	79	2.94	3.73
MB/SB	105	4.02	3.83
SB	125	4.93	3.93
SB/HB	140	5.64	4.03
HB	158	6.52	4.13
HB/T	175	7.40	4.23

cultivated fields occupy the most productive sites, which reduces the mean values of G and K. The reduction is noticeable in the southern boreal zone and particularly in the hemiboreal zone. If fields had not been cleared the series of G (m^3 ha^{-1} a^{-1}) might have been even, increasing from one boundary to another in steps of 2.1, beginning from 0 at the timberline and ending at about 8.4 at the southern boundary of the boreal main zone. Applying the values of G/K in Table 1 higher values of K (as 110 for MB/SB, 156 for SB/HB and 199 for HB/T) are obtained.

Let us travel northwards along a sample of longitudes and determine the locations of the boundaries between the ecoclimatic zones at these longitudes (Fig. 1 and Table 3), determined by the values of G that are obtained as function of climatic variables as given by Eq. 19. In this section, these locations are reported in the context of the climatic variables involved. The detailed locations are important for readers who apply these results in any particular region, while the reader who intends to have a general conception of the boreal zone system and the compatibility of the climate- and vegetation-based delimitation, is recommended to pass over Table 3, and move on to the next section "On the accuracy of the results".

In Fennoscandia, boreal zones are located at particularly high latitudes; higher than anywhere in the hemisphere. Farthest west, at 5–6°E, the southwestern coast of Norway, we meet the southern boundary of the hemiboreal zone as far north as 60.4°N. The beneficial climate there creates a very long vegetational period, mild winters and very little or no soil frost. In such a maritime climate at such latitudes, the vegetational period and the effective temperature sum shorten rapidly with decreasing mean temperatures brought about by increasing altitude. This in turn causes a rapid succession of zones. Also in other parts of Fennoscandia L and V are rather sensitive to altitude. For this reason, the rather strong topographical features in Fennoscandia cause irregular and complicated features in the system of boreal zones. Travelling northwards along any longitude across Fennoscandia, the succession of zones does not occur in a regular order.

Take two examples. Travelling northwards in southwestern Sweden along the 13°E longitude, beginning from 56.3°N latitude, the hemiboreal gives way to the southern boreal when reaching the Småland highlands but returns to the hemiboreal zone when descending to the valley of lake Vänern. Then, ascending towards the Scandian mountain range, we move stepwise to the southern boreal, middle boreal and northern boreal zones. Descending from the mountain range towards the Norwegian coast, we arrive in a reversed order to the southern boreal zone at the Atlantic coast at 65.9°N. At the 67.0°N, i.e., between the mainland coast and the Lofoten Islands, we return to the middle boreal zone in a regular order.

Travelling northwards along the 22°E longitude, beginning from the 60.7°N latitude in southern Finland, we leave the southern boreal zone when ascending above 150 m level at 62.2°N, but descending towards the coastland of the Gulf of Bothnia, we come back to the southern boreal zone. At the northern end of the Gulf of Bothnia, we arrive back to the middle boreal zone, and so on to Lapland and the northern boreal in a regular order. Strictly speaking, north of the Gulf of Bothnia we do not follow the 22°E longitude exactly but proceed northwards between the 23°E and 24°E longitudes where the observation network is denser. Descending to the Norwegian coast, we again meet pockets of middle boreal climate and vegetation at the ends of the Kvenanger and Skibotten fjords. The occurrence of middle boreal conditions so far north, about 70°N, is unique in the northern hemisphere.

Considering that F is mainly a function of frost sum and snow depth, thick snow cover and abundant precipitation in winter are ecological advantages so that the boundaries between the southern and middle boreal, middle and northern boreal, and northern boreal and hemiarctic zones, are moved somewhat northwards by regional maxima of precipitation and snow depth. Thick snow cover in the highlands also largely eliminates the disadvantage of low air temperatures.

Following the boundary between the southern and middle boreal zones eastwards we may note that the disadvantageous effect of soil frost increases from the Norwegian coast to the regions around the Gulf of Bothnia where snow cover is thin in relation to frost sum because precipitation is small in the lee of the Scandinavian mountain

Table 3. The climatic locations of the boundaries between the boreal zones in Europe at various longitudes (°E), latitudes (°N), and the height (m a.s.l) concerning the variables of the basic equation for the boreal nature: *L* = the effective temperature sum, *V* = the duration of the thermal vegetation period, and *F* = the winters' greatest soil frost depth. All values are climatic means for the period 1961–2000, or reduced to it. The accurate longitudes (°E), given as subscripts of the location codes may differ more or less from those in the titles of the columns due to the location of available observations or the occurrence of points on open sea. The location codes are denoted by capitals as follows: A = the boundary between the hemiarctic and arctic zones, B = the boundary between the northern boreal and hemiarctic zones, C = the boundary between the middle and northern boreal zones, D = the boundary between the southern and middle boreal zones, E = the boundary between the hemi- and southern boreal zones, and F = the southern boundary of the hemiboreal zone.

	Location of zone boundaries						
	6°E	13°E	22°E	28°E	40°E	50°E	70°E
Code				$A_{25.9}$			$A_{66.5}$
Latitude				68.8			67.7
Height				600			40
L				410			555
V				99			104
F				43			60
Code				$B_{25.9}$			$B_{66.5}$
Latitude				68.8			65.7
Height				370			40
L				540			675
V				112			111
F				37			52
Code	$C_{5.6}$	C_{13}	$C_{23.8}$	C_{28}	C_{41}	C_{50}	$C_{72.6}$
Latitude	60.4	61.8	67.0	65.6	65.1	64.0	62.0
Height	750	530	120	250	120	200	40
L	600	745	845	800	790	775	910
V	158	139	131	131	132	123	123
F	10	22	31	26	25	22	37
Code		C_{13}	$C_{23.4}$				
Latitude		65.2	70.0				
Height		370	5				
L		685	740				
V		137	135				
F		14	20				
Code	$D_{5.5}$	D_{13}	D_{22}	D_{28}	D_{40}	D_{50}	D_{69}
Latitude	60.4	60.5	62.2	63.5	62.7	60.8	58.7
Height	420	330	150	130	100	150	55
L	880	1040	1050	1070	1055	1100	1270
V	178	166	158	153	148	146	152
F	5	21	20	21	18	22	45
Code		D_{13}	D_{22}				
Latitude		65.9	63.0				
Height		80	20				
L		900	1125				
V		173	162				
F		7	30				
Code		D_{13}					
Latitude		67.0					
Height		20					
L		835					
V		178					
F		0					

continued

Table 3. Continued.

	Location of zone boundaries						
	6°E	13°E	22°E	28°E	40°E	50°E	70°E
Code	$E_{5.4}$	E_{13}	E_{22}	E_{28}	E_{40}	E_{50}	E_{73}
Latitude	60.4	59.6	60.7	60.5	57.8	57.9	54.5
Height	210	110	40	10	120	180	110
L	1110	1240	1300	1260	1335	1365	1550
V	194	181	180	173	168	161	165
F	0	10	17	11	18	20	44
Code		E_{13}					
Latitude		57.9					
Height		220					
L		1190					
V		186					
F		5					
Code	$F_{5.3}$	F_{13}	F_{22}	F_{28}	F_{40}	F_{50}	
Latitude	60.4	56.3	56.3	53.7	53.9	54.6	
Height	35	40	20	180	120	100	
L	1355	1475	1495	1585	1635	1685	steppe
V	231	197	200	188	182	178	
F	0	5	8	15	21	23	

range. At the 28°E longitude, soil frost is thinner again, because at the boundaries S/M and M/N the precipitation-decreasing effect of the mountain range is already small, and local orographical lifting is effective. From the 28°E longitude eastwards up to the 50th longitude, frost sum increases while precipitation gradually decreases. The decrease in precipitation eastwards is, however, so small that snow depth even increases. Consequently, the depth of soil frost increases only slightly. Over the Urals, precipitation, however, decreases more steeply eastwards so that snow depth does not increase while frost sum continues to increase. So, soil frost in western Siberia is clearly deeper than on the European side of the Urals. Following the boundary between the southern and middle boreal zones eastwards to the 70°E longitude, the value of *F* is as high as 55 cm, although the latitude is only 58.7°N. Correspondingly, the latitude of the boundary between the middle and northern boreal zones at the 72.5°E longitude is only 62.0°N (while that at Alta with mild winters is 70.0°N). Given the crucial importance of soil frost for the boundaries between the southern and middle boreal zones and middle and northern boreal zones, it is here the most significant variable for measuring the continentality of the climate. The increase of soil frost and continentality eastwards is neither uniform because of the impact of mountain ranges on precipitation and snow depth. For example, the regions adjacent to the Gulf of Bothnia, situated in the lee of the Scandinavian mountain range, have a relatively thin snow cover and deep soil frost. They can be therefore characterized as a "mini Siberia", edged by more maritime South- and East-Finnish regions.

On the accuracy of the results

Several botanists have independently recognised these zones and the locations of their boundaries, and so they must be zones of significant gradients in the occurrence of species. Comparing the locations of the climatic boundaries under consideration with the corresponding locations of forest vegetation zones at these longitudes, as determined by botanists Sjörs and Tuhkanen, it was found that in all cases the climatic points deviate by less than 30 km, with most deviations falling in the range of 0 to 20 km.

The result, which cannot be due to chance, shows that the basic material was accurate enough for the task in hand. Let us, however, examine the accuracy of the meteorological variables. Temperature observations, used to obtain the sum of effective temperatures L and duration of the vegetational period V, are accurate. However, the accuracy of L and V depend on how representative the observation sites are of their region. Any error is somewhat smoothed because in regions with dense station networks any strongly deviating station could be identified and ignored. In any case, values used in Eq. 19 to locate the boundaries were a function of spatial interpolation; the weighted means of at least two values. Another potential source of error in L and V is the reduction of time to the period 1961–2000. The error in the correction of $L_{1961–1990}$ of +15 °C d and that for $L_{1931–1960}$ of –15 °C d could in some regions be as large as –20 °C d or +20 °C d. According to Eq. 19, the corresponding errors in G are –0.10 and +0.10 $m^3\ ha^{-1}\ a^{-1}$, i.e. they are insignificant. This value corresponds to an average decrease of G over a distance of 20 km (0.2 degrees of latitude) northwards. The values of V were practically the same in all periods and reductions were approximated as zero. Suppose, however, that there are some regions where V has changed by as much as four days between the periods. According to Eq. 19, the corresponding effect upon G would also be small, at 0.05 $m^3\ ha^{-1}\ a^{-1}$. Consequently, the average reductions in L, eliminating systematical errors, are more than adequate.

We now examine the accuracy of P and D, and the accuracy of F as their function. Suppose that in a northern Russian region the reduction of P is –5% or –80 °C d from the period 1961–1990 to the period 1961–2000, whereas the correct reduction should be 0. Assuming a typical value for D in Eq. 9 to be 57 cm, an error of 2.1 cm is found in F causing an error of –0.09 $m^3\ ha^{-1}\ a^{-1}$ in G. Suppose the actual value of D is 50 cm instead of 57 cm (corresponding to the winters' maximum water equivalence of snow cover of 152 mm instead of 172 mm), the error in F is then –6.1 cm, and the corresponding error in G is +0.28 $m^3\ ha^{-1}\ a^{-1}$. The boundary in question is then placed too far south by 0.5° of latitude, which is 15% of the average spacing of the zones. All in all, the inaccuracy of D in Russia is the largest and only noticeable potential source of error, albeit not a serious one. On the other hand, extremes in the fertility of soils may cause deviations to the order of 0.5 to 1.0 $m^3\ ha^{-1}\ a^{-1}$ in G and shift zone boundaries by about 1° of latitude. The greatest differences in the locations of the boundaries established by various botanists are of this magnitude.

We may conclude that each forest vegetational boundary at various latitudes could be placed, very accurately at the locations determined by botanists, on the basis of productivity calculated merely as a function of climatic variables. We may also conclude that Eq. 19 can be applied successfully in the boreal zone as whole from the border of the temperate zone in the south to the timber line in the north, as well as from the Norwegian coast in the west to Siberia in the east.

Productivity and evapotranspiration in forests by zones

Explaining the annual forest evapotranspiration E_f for the period 1961–1990 for 40 drainage basins in the middle and southern boreal zones (Hyvärinen *et al.* 1995) by the productivity of forests (Ilvessalo 1960), we obtain

$$E_f = 172 + 48.4G \qquad (21)$$

with a correlation coefficient of 0.94.

Applying this equation to the values of G for the zone boundaries beginning from the boundary between the northern boreal and hemiarctic zones and the boundary between the hemiboreal and temperate zones (Table 1), the guidance values of E_f (mm) for these boundaries are 172, 271, 367, 444, and 530, respectively. The zonal average for the middle boreal is 313 mm and that for the southern boreal 414 mm.

Replacing G in Eq. 21 with the one given by Eq. 19, we obtain Eq. 22 for E_f

$$E_f = 51 + 0.267L + 0.58V - 2.2F \qquad (22)$$

Equation 22 enables the estimation of regional evapotranspiration values in the boreal forests merely as a function of climatic variables.

However, the equation does not apply if forest growth deviates appreciably from the productivity, e.g. due to heavy loggings or a skewed age class distribution. Note also that for exceptionally fertile or barren soils E_f is 30 to 50 mm higher or lower than obtained from Eq. 22.

Equation 21 indicates that a considerable spatial gradient occurs for G across the boundary between the southern and middle boreal zones, and also that the humidity of the climate during the vegetational period increases sharply. This is in accordance with the gradient of the areal proportion of mires and mire vegetation.

On even, undrained middle and northern boreal areas, the excess of water seems to reduce the value of G by about 0.7 m^3 ha^{-1} a^{-1}. This corresponds to a reduction of 35 mm in the annual evapotranspiration. As mires in such areas cover about 60% of total land area and open fens 20%, the high evapotranspiration from surfaces of shallow water layers occurring largely on fens cancels out the low evapotranspiration in the poorly productive forests.

On winter climate and productivity of forests

Equation 22 also shows that a decrease of soil frost depth by 10 cm and frozen water by 30 mm enhances the annual evapotranspiration by about 22 mm. Such a decrease in F is caused by an increase of 10 cm in D (mean snow depth during the soil frost period) or 30 mm in the winters' maximum water equivalence of snow cover. Such an increase of snow cover is caused by the increase in precipitation independently of variations in the frost sum in a climate in which the frost sum exceeds 1500 °C d on average. In the case of milder winter climates, an increase in precipitation is usually associated with higher winter temperatures. The increased thaw in such cases largely eliminates the effect of the increased precipitation on snow depth (Solantie and Drebs 2001). With frost sums at 800 to 1500 °C d, the common effect of higher temperatures and reduced snow depth is an appreciable increase in the soil frost depth and the lower productivity of the forests. For frost sums between 300 and 800 °C d the effect is weak. On the other hand, a positive effect of higher temperatures on forest productivity may be appreciable in the maritime hemiboreal and southern boreal areas of the mildest and moistest winters (F < 300 °C d). Soil frost is insignificant in these regions, the duration of the vegetation period is long, while the change of temperatures in spring and its decrease in autumn are slow. For this reason, both the duration of the vegetation period and the effective temperature sum are sensitive to the changes in the mean temperature in November and early April. The fact that in these regions the growth of forests has increased appreciably during the last hundred years (Mielikäinen 1996) can be explained by milder cold-season temperatures.

Disadvantage of soil frost for perennials

Boreal forest trees are well adapted to tolerate hard frosts. Soil frost is therefore a more important factor for the productivity of the boreal nature than low air temperature in winter as such. The addition of soil frost as an important variable for explaining the distribution of boreal species enables us better to understand the regional distribution of perennials. Some plant species have greater sensitivity to soil frost. Typically, such species are perennials with a shallow and strong root system. The upper soil is both rich in nutrients and crucial to plant reproduction. For such species, Eq. 19 applies only if the coefficient of F is enlarged. Let us take as an example the northern limit of *Pteridium aquilinum*, corresponding to a coverage of 0.1% (Reinikainen 2000). The northern limit of this species is a constant both in Finland and in the Lofoten Islands if the coefficient of F is –0.1200 instead of –0.0455. Reinikainen classifies this species as maritime because it occurs in the Lofoten Islands within the middle boreal zone (at the 68°N latitude), while in Finland its northern limit extends to the southern boreal zone. The northern boundary of this "maritime" species in Finland runs from South-West to North-East! A similar case is the limit of coverage of 0.1% of another large-rooted perennial *Fragaria vesca* (Silferberg and Reinikainen 2000). A third example is *Anemonia nemorosa* (Reinikainen 2000). Its northern limit in Europe is very similar to that of *Pteridium aquilinum*. It is, however, rare in the southeastern regions of Finland, because it apparently demands nutrients associated with clayey soils. The fact that its occurrence has appreciably declined between the inventories 1951–1953 and 1985–1986 and further still in 1995 in regions west of the 23.5°E longitude but not at all to the east of it (Reinikainen 2000) may be due to soil frost conditions. The particular disadvantage of a deep soil frost for this species is due to its very early onset of growth and blooming, which obviously demands warm soil during the previous winter. In Varsinais-Suomi county, west of the 23.5°E longitude, the mean of F, calculated with Eq. 5 by using gridded snow depth values, during the period 1947–1963 was 11 cm, while during the period 1964–1998 it was 20 cm. In Uusimaa county east of the 23°E longitude, the corresponding values are 8 cm and 13 cm. In the western area, soil frost was unusually deep in the years 1978, 1979, 1980, and 1987; in each of these years the mean of F in the forests at the two western soil frost stations Jokioinen and Mietoinen exceeded 70 cm; a similar figure was found on open places, except in 1979. On the other hand, in the east such values were not observed, either in forests or on open places (Huttunen and Soveri 1993). Concerning herb vegetation in the southern boreal zone, Tonteri (2000) noted that its coverage in southwestern areas has generally declined since 1951–1953 but not farther east. This observation is also in accordance with the behaviour of winter climate. In the winter 1978–1979, the damage to dwarf shrubs was at its severest and most extensive. From 14 to 17 and from 29 to 31 December 1978, frosts with screen level temperatures of –34 to –37 °C occurred over most of southern and central Finland. During one or both of these periods in all regions west of 24°E, snow cover was absent or too thin to protect dwarf shrubs from killing frost. Farther east, damage occurred due to thin snow cover. Most of above-snow parts of bilberry (*Vaccinium myrtillus*) were killed by frost, and the subsequent berry yield was totally lost over large areas. A detailed cartographic analyse of the fatal conditions caused by snow cover and frost was carried out and compared with the crop failure of bilberry using the berry yield inquiry of the Pellervo society by Solantie (1980). The vegetative coverage of bilberry was very low in western areas in 1985 compared with the coverage in 1951–1953 (Salemaa 2000). This reflects below-ground frost damage, the repair of which took many years. An old Finnish folklore “Bare ground at New Year means a loss of berries next summer” recognises the relationship between ground frost and plant damage.

Forest productivity by climatic zones in relation to the dominant height of forest stands, surface inversions and minimum temperatures

The average height of tree stands increases with the increase of the volume and productivity of growing stands. From the southern boreal zone northwards, forests and mires cover appreciably greater areas than cultivated fields. Consequently, in weather conditions of cold surface inversions, the mean height of stands in forests and mires is a crucial factor governing the steepness of the inverse temperature gradient in the lowest air layer and the resultant minimum temperatures. In tall stands, the rather isothermic layer between the main radiating surface formed by the crown level and the ground is much thicker and warmer compared with the air layer beneath low growth and sparse stands on mires where the main radiating surface is the peat or snow cover on the ground. Inversions in forests, particularly in dense and tall stands, form later during light winds than on mires because the turbulence at ground level also ceases later. Mires are more common in the middle boreal and forest stands are appreciably lower than in the southern boreal. The mean monthly minima are therefore appreciably lower in the middle boreal, where night frosts can even occur in July. Night frosts in July are very rare in the southern boreal zone.

It is therefore useful to know the mean height of growing stands in various zones. For the southern and middle boreal zones in Finland, consider that 90% of stands in both the SB and the MB are dominated by coniferous species. Tamminen (1993) studied the dominant height of 100-year-old stands (H_{100}) of Norwegian spruce and Scots pine in various site-index classes at 1248 sites in ten municipalities, six of these located in the SB, two in the MB and two in their boundary zone. Karlsson (1996) calculated the same variables for experimental plots in the national forest inventories 1971–1975, 1977–1983, and 1987–1992. The results were presented both as map analyses and means for five forestry board districts, of which two were in the southern boreal zone (Pohjois-Savo and Keski-Suomi), two in the middle boreal zone (Keski-Pohjanmaa and Pohjois-Pohjanmaa), and three in the boundary zone (Etelä-Pohjanmaa, Pohjanmaa, and Pohjois-Karjala). The results by Tamminen and Karlsson are summarised in Table 4. Calculations of the weighted means take into account that spruce is as common as pine in the southern boreal while the pine-spruce ratio is 4:1 in the middle boreal. In the boundary zone, the frequencies are the means of those of the southern boreal and middle boreal.

The results of Tamminen and Karlsson are quite similar. Only in the southern boreal are Tamminen's values slightly higher. Because the plots in the southern boreal studied by Karlsson were located in the northernmost part of the zone, Tamminen's values are adopted here. Thus the corresponding mean values for stands in the southern boreal and in the middle boreal become 25.0 m and 18.5 m, respectively. These figures show that in the middle boreal spruce suffers from climatic factors and is located on the most favourable sites, while in the southern boreal spruce displaces pine on sites with high site-index values. The relationship of the dominant height at various age classes to the dominant height at H_{100} was obtained on the basis of studies by Nyyssönen (1954), Koivisto (1959), Mielikäinen (1980), and Gustavsen (1980). Accordingly, the ratios of the heights of 20-, 60- and 140-year-old stands to H_{100}, for example, are 0.25, 0.82 and 1.10 in the southern boreal, while in the middle boreal the corresponding values are 0.20, 0.80 and 1.11. The figures show that the ratio of the dominant height in the middle boreal to that in the southern boreal is 1/2 for 30-year-old trees but increases with age to 2/3 for 100-year-old trees. Further, we may approximate the dominant height of poorly-productive stands to be 7 m. These dominant heights may then be weighted by the areal proportions of the various aged-productive forests, poorly-productive stands and waste land (Yearbook of forest statistics 1993–1994). In this way, the mean dominating height of stands in forests and mires in the southern boreal is found to be 16 m and 10.5 m in the middle boreal, the latter being 2/3 of the former. The corresponding mean volume of the growing stands in the forests and mires in southern boreal is 117 m^3 ha^{-1} (in the forests 125) while in the middle boreal it is 64 m^3 ha^{-1} (in the forests 79), the latter being 55% of the former. The mean volume of stem wood in each one-metre layer of space under the canopy, that can be related to the density of the forests, is 7.3 m^3 ha^{-1} in the southern boreal and 6.1 m^3 ha^{-1} in the middle boreal, the latter being 83% of the former. On this basis, the map of the areal distribution of the growing stands in the forests (m^3 ha^{-1}) in Finland (Tomppo 2000) can be approximately converted to a map of the mean height of growing stands (Fig. 6) by multiplying the former values in grid points by the relation of the ratio of the mean height to the mean volume in the respective zone. This ratio = 0.13 both in the southern boreal and middle boreal (16/125 (SB) = 10.5/79 (MB) = 0.13).

Prior to the large-scale drainage measures on mires for timber production, the difference in the dominant height of forest stands between the ecoclimatic zones in Finland was greater than at present. Despite these measures, stands are appreciably lower and sparser in the middle boreal than in the southern boreal. For this

Table 4. Dominant heights of pine (*Pinus silvestris*) and spruce (*Picea abies subsp. abies*) for the southern and middle boreal zones and their boundary zone, based on results by Tamminen (1993) and Karlsson (1996).

	Tamminen	Karlsson
Southern boreal, pine	22.7	22.8
Southern boreal, spruce	27.4	25.2
Southern boreal, weighted mean	25.0	24.0
Boundary belt, pine	19.6	20.3
Boundary belt, spruce	24.4	22.4
Boundary belt, weighted mean	21.4	21.1
Middle boreal, pine	18.4	18.1
Middle boreal, spruce	18.5	19.0
Middle boreal, weighted mean	18.4	18.3

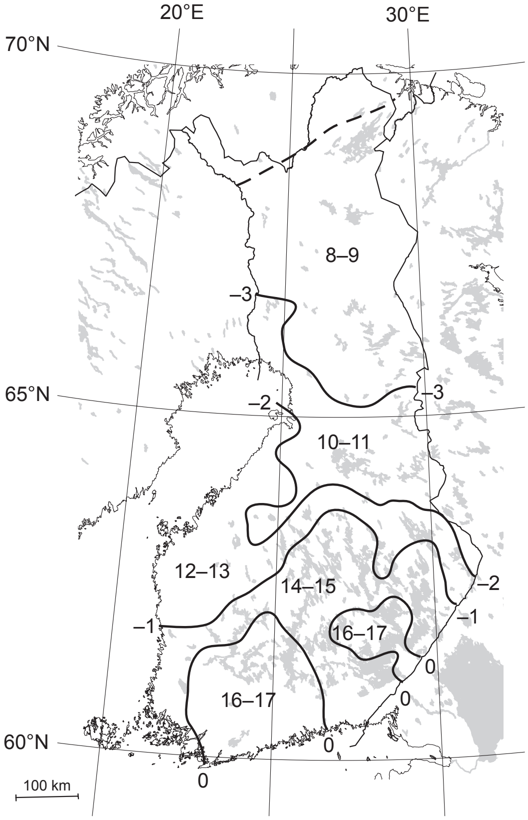

Fig. 6. The mean height of growing stands in forests and mires (m), and its effect on the minimum temperatures in situations of surface inversion during the vegetation period as compared with the mean in the southern boreal zone (°C).

reason, surface inversions at night and in the winter become shallower but sharper in the middle boreal than the southern boreal.

Monthly minimum temperatures during the vegetational period invariably occur during situations of surface inversions. Their means in summer months (June, July and August) 1961–1990 at stations in the southern and middle boreal zones were studied, together with corresponding means for the whole vegetation period, i.e. May to September (Solantie and Drebs 2000). In order to obtain the effect of forests and mires on the minima, stations adjacent to water bodies and those at extreme hill or valley locations were ignored. All values were reduced to 100 m a.s.l. and then examined by linear regression analyses as a function of latitude for each zone. The difference in the effect of the growing stands in minima between the zones was approximated by the difference in the solutions of both equations at the 63°N, being 2.22 °C in the summer and 2.64 °C during the vegetational period. In March, the difference is even greater. Thus, during the vegetational period we have $\delta M/\delta H^* = 2.6/(16 - 10.5) = 0.48 \sim 0.5$ °C m^{-1}. Correspondingly, for the duration of the frost free period ff we have a difference of 27.9 days, and $\delta \mathrm{ff}/\delta H^* = 27.9/(16 - 10.5) = 5.1 \sim 5$ d m^{-1}.

Quantitative relations between boreal nature variables

The average effect of the height of tree stands on minimum temperatures in forests and on mires in inversion situations during the vegetation period is one climatic application of the results (Fig. 6). Considering that numerical estimations of other interactions involved in the boreal system are also useful, it is practical to create a table with partial derivatives of boreal nature variables with respect to each other. The values in Table 5 are calculated on the basis of coefficients in Eq. 20 for the variables in question, and in the other cases as relations of differences between the values in the southern and middle boreal zones in Finland. The results therefore apply best to Finnish conditions but they also provide a guidance for other areas.

Conclusions

This paper has shown that the boundaries between two boreal zones, or both edges of the main boreal zone, correspond to a certain forest productivity (m^3 ha^{-1} a^{-1}), and that the forest productivity can be given as a function of three climatic variables, effective temperature sum, duration of the vegetational period and the greatest depth of soil frost. The latter can be given as a function of frost sum and the average snow depth during the soil frost period. It was shown that these results apply from Norwegian west coast to western Siberia, and from the boundary of the temperate zone to the boundary of the hemiarctic zone (also called the timber line). Relating evapotranspiration to the productivity

Table 5. Partial derivatives of variables for boreal nature, both climatic and biological, with respect to each other. G = productive capacity of forests (m^3 ha^{-1} a^{-1}), G^* = productive capacity of forests and mires(m^3 ha^{-1} a^{-1}), $\approx 0.82\ G$ in the MB, $\approx 0.94\ G$ in the SB, K^* = volume of growing stands in forests and on mires (m^3 ha^{-1}), K = volume of growing stands in forests (m^3 ha^{-1}), H^* = mean height of stands in forests and on mires (m), H = mean height of stands in forests (m), F = mean maximum soil frost depth (cm), D = mean snow depth on 15 March (cm), P = frost sum on the snow surface (–°C d), M = minimum temperature in inversion situations (°C), ff = duration of frostless period (d), L = effective temperature sum above +5 °C (°C d), and E = mean annual evapotranspiration (mm).

$\delta F/\delta D \approx -1.0$	$\delta F/\delta P = 0.03$		
$\delta G/\delta F \approx -0.045$	$H/\delta F = -0.11$	$\delta K/\delta F = -1.04$	
During the vegetation period	$\delta M/\delta F = -0.04$	$\delta M/\delta K = 0.04$	$\delta M/\delta H^* = 0.5$
and in March	$\delta M/\delta F \approx -0.05$	$\delta M/\delta K \approx 0.05$	$\delta M/\delta H^* \approx 0.6$
Further	$f/\delta K^* = 0.5$	$\delta ff/\delta H^* = 5$	$\delta E/\delta G = 48$
$\delta G/\delta L = 0.0065$	$\delta H^*/\delta L = 0.018$	$\delta K/\delta L = 0.145$	
$\delta H^*/\delta K^* = \delta H/\delta K = 0.103$	$\delta H^*/\delta G^* = \delta H/\delta G = 2.4$	$\delta G^*/\delta K^* = \delta G/\delta K = 0.043$	

in the form of an equation, and substituting the productivity as a function of climatic variables, guidance values of evapotranspiration in the various boreal zones can be obtained as function of climatic variables only.

Beginning with 0 m^3 ha^{-1} a^{-1} at the boundary between the hemiarctic and northern boreal and ending with 7.4 m^3 ha^{-1} a^{-1} at the boundary between the hemiboreal and temperate zones, the boreal zones seem to have a standard width of 1.85 m^3 ha^{-1} a^{-1} in terms of forest productivity. The relative productivity (in relation to the volume of growing stands) seems to increase evenly from 3.63% at the boundary between the northern and middle boreal by zonal steps of 0.20% to 4.23% at the boundary between the hemiboreal and temperate.

A central result of this study is the observation that climatic and vegetational zones are equivalent. Such equivalence enables an understanding of the interaction between the biological and physical regime of boreal nature. It may therefore be sensible to speak of ecoclimatic zones rather than climatic or forest vegetational zones that are tied to a specific discipline. The term "ecoclimatic" has already been suggested by the Canada committee of Ecological Land classification, Ecoregions working group (1989).

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