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Charts of the climatic impact of the drainage of mires in Finland

Karttoja suo-ojitusten vaikutuksesta Suomen ilmastoon

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Widespread drainage measures, which were carried out mainly in the period 1950–1990 on Finnish mires, have had significant climatic consequences, part of them being temporary, part permanent. The aim of this study was to prepare charts of these climatic effects by combining three sources of knowledge: (1) the climatic effect of drainage (e, °C), as given by (Solantie 1994, 1998) for a 100% mire area in the climatically most affecting stage, (2) fresh grid-square statistics of the proportion of drained mires compared with the total area, and (3) annual statistics of the proportion of drained mires in various stages having characteristic climatic effects, compiled by the Finnish Forest Research Institute. Three charts show the maximum cooling effect of peatland drainage in Finland during the first 15 years after the drainage in the period 1973–1982, as drained mires in such a stage of drainage were then most common. Two charts show the warming effect after successful afforestation and canopy closure; the canopy acts as a radiation shelter and a mixing generator for the air beneath. In the middle boreal natural zone, that most heavily drained, the mean monthly minimum temperatures in the period 1973–1982 were reduced by 1.5°C and the yearly frost-free period was shortened by 17 days. As a result of successful afforestation, the annual minimum temperature in the middle boreal zone will be raised by 2°C to 3°C by the year 2005.

Keywords: climate, forestry drainage, mire

INTRODUCTION

“Mire” is here defined as an area having a peat layer thicker than 30 cm, or having thinner peat but mire vegetation. After drainage, a vegetation succession starts towards to the typical forest vegetation of mineral lands. The successive stages of drained mires are called here “recently drained”, “transforming” and “transformed”.

During the “recently drained” stage the shield of trees is partly or totally lacking. The topmost peat layer is drier than in the natural state, and heat exchange through it is diminished due to the thermal insulation of rather dry peat in summer. In winter, the snow cover acts as a layer of thermal insulation; this also occurs naturally on mires in their undrained stage. Consequently, during calm and clear weather at night the air over mires in the “recently drained” stage becomes strongly cooled, and a layer of strong inversion (i.e. an air

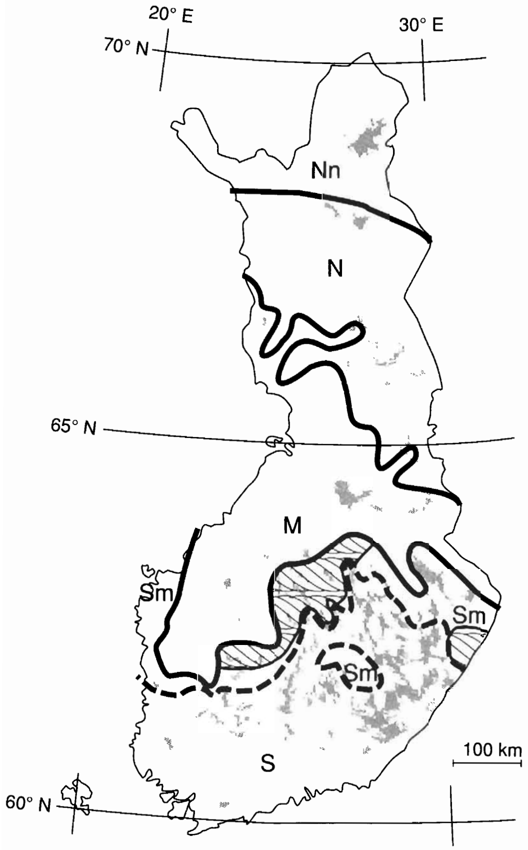

Chart 1. The main forest vegetational zones in Finland (Kalela 1961). S = the southern boreal zone (Kalela's "Etelä-Suomi"); M = the middle boreal zone (Kalela's "Pohjanmaa-Kainuu"); N = the northern boreal zone proper (Kalela's "Perä-Pohjola"); Nn = the northern part of the northern boreal zone (Kalela's "Metsä-Lappi"). The dotted line shows the southwards extension of the boundary belt between S and M, denoted Sm ("Pure" S comprises the areas where the annual productive capacity of good forest land exceeds 4.0 m^3 per hectare (Ilvessalo 1960, Chart 30) and the effective temperature sum L > 1100°Cd (1931–1960, Solantie 1974) or where L > 1200°Cd). The hatched area denotes a drainage proportion of over 80 % within Sm.

Kartta 1. Suomen päämetsäkasvillisuusvyöhykkeet (Kalela 1961). S = eteläboreaalinen vyöhyke (Kalelalla "Etelä-Suomi"); M = keskiboreaalinen vyöhyke (Kalelalla "Pohjanmaa-Kainuu"); N = pohjoisboreaalinen vyöhyke (Kalelalla "Perä-Pohjola"); Nn = Pohjois-boreaalisen vyöhykkeen N pohjois-osa (Kalelalla "Metsä-Lappi"). Katkoviiva on etelä-ja keskiboreaalisen vyöhykkeen vaihettumiskaistaleen Sm eteläraja ("Puhdas" S käsittää alueet, joissa kasvullisen metsämaan puuntuottokyky ylittää 4.0 m^3 ha^{-1} vuodessa (Ilvessalo 1960) ja joissa tehoisan lämpötilan summa L > 1100°Cd (1931–1960, Solantie 1974), tai joissa L > 1200°Cd). Viivoitus kuvaa yli 80%:n ojitusasteen aluetta rajakaistaleessa Sm.

layer in which the temperature increases more steeply upwards than generally) often develops in the air above the mire. During the "transforming" stage the shelter of trees is increasing, whereas in the "transformed" stage it has been completed. After that, the cooling effect is effectively reduced, both in summer and in winter, due the effect of the tree stand.

The rise of temperature with stand development can be explained as follows. The main surface sending long-wave radiation out to the sky is lifted due to stand development from the ground surface to the canopy. As air is cooled at the canopy by the emitting long-wave radiation, it sinks down, stirring the air layer beneath the canopy. Because the canopy is also rougher than the ground surface, and rougher still than a snow cover, even a slight breeze is enable to stir air around the canopy, further reducing the inversion and raising temperatures close to the ground; before stand development the cold air would lie undisturbed on the ground.

The nightly warming in summer due to stand development is of the same order as the previous cooling, and minimum temperatures may rise close to the level that prevailed before drainage (Solantie 1994, 1998). In winter, due to stand development, minimum temperatures will rise to appreciably higher values than those prevailing before drainage (Solantie 1994, 1998).

The widespread drainage measures, carried out on Finnish mires mainly in the period 1950–1990 and most intensively in the late 1960's and early 1970's, are now practically accomplished. These measures have had significant consequences on the regional climate (Solantie 1994, 1998), part of them being temporary, part permanent. Here they have been estimated as proportional to the ratio of the affecting area to the total area (Solantie 1994, 1998).

Drained mires occur mostly in the middle boreal forest vegetation zone (Charts 1 and 2). This is basically due to climatic reasons: in the northern boreal zone the climate is too severe for successful drainage, while in the southern boreal zone, evaporation exceeds precipitation in summer to such an extent that mires only occur to a relatively limited extent. Besides the effect of widespread drainage, logging, which may enhance the climatic effects of drainage, has also been more

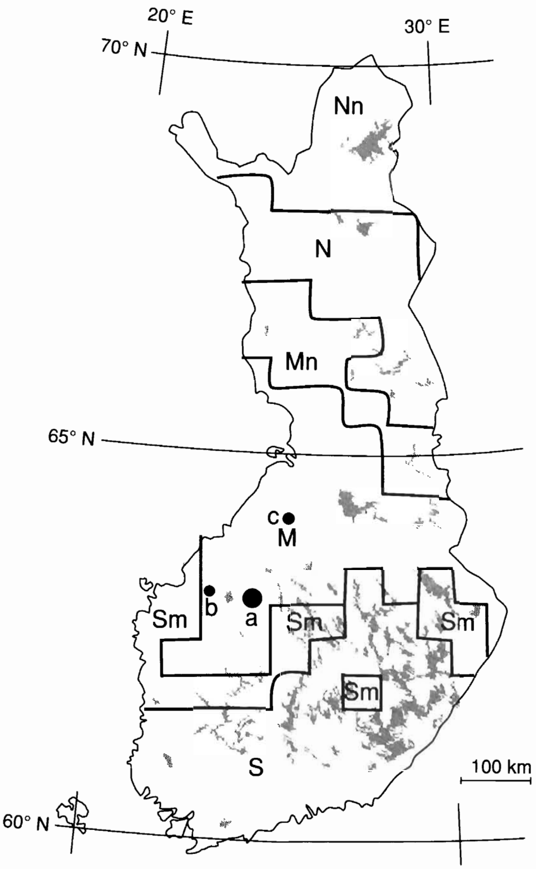

Chart 2. The main forest vegetational zones in Finland with boundary belts, showing the square grid used, and the locations of the main observation station Möksy (a) for the climate effect of drainage, and the reference stations (Kauhava (b) and Haapavesi (c)). S = the southern boreal zone proper; M = the middle boreal zone proper; N = the northern boreal zone proper; Sm = the northern edge of zone S; Mn= the boundary belt between zones M and N; Nn = the northern part of the northern boreal zone.

Kartta 2. Suomen päämetsäkasvillisuusvyöhykkeet rajakaistaleineen, sovitettuna laskentaruudukkoon, sekä ojituksen ilmastovaikutustutkimuksen päähavaintoasema Möksy (a) ja vertailuasemat (Kauhava (b) ja Haapavesi (c)). S = puhdas eteläboreaalinen vyöhyke; M = puhdas keskiboreaalinen vyöhyke; N = puhdas pohjoisboreaalinen vyöhyke; Sm= vyöhykkeen S pohjoisreuna; Mn = vyöhykkeiden M ja N rajakaistale; Nn = vyöhykkeen N pohjoisosa.

widespread in the middle boreal zone (Chart 3). Thus, the strongest effects would be expected to occur in the middle boreal zone, albeit the proportions of drained mire area compared with the total mire area (%, Chart 4) are about the same in the southern and middle boreal zones.

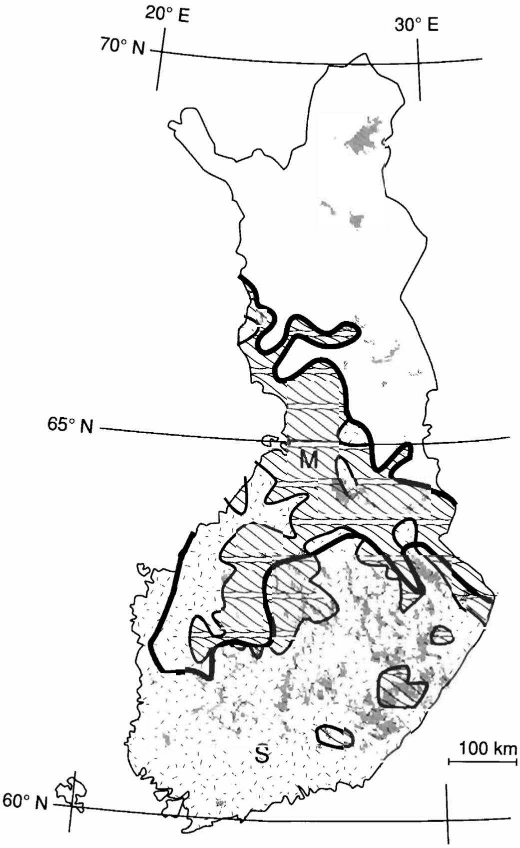

Chart 3. The regions within the middle boreal (M) and southern boreal (S) zones during the period 1971–1975 where the combined percentage of regeneration areas, seed-tree, seedling and sapling stands comprised less than 30% of the forest area (dotted), and the regions within those zones where that percentage exceeded 30% (hatched) (from Salminen 1981).

Kartta 3. Ne etelä- (S) ja keskiboreaalisen (M) vyöhykkeen alueet, joissa aukean alan, siemenpuumetsiköiden sekä taimisto- ja riukuvaiheen metsiköiden yhteinen osuus metsämaan alasta 1971–1975 oli alle 30% (pilkuin), ja ne näiden vyöhykkeiden alueet, joissa tämä osuus oli yli 30% (viivoin) (Salminen 1981).

The purpose of this study was to calculate the effects of the drainage of mires on some climatic variables in Finland, and to express these effects in the form of charts. The results were given as the general climatic effect per unit of the total area (including land and inland waters); each variable considered was obtained by multiplying the cli-

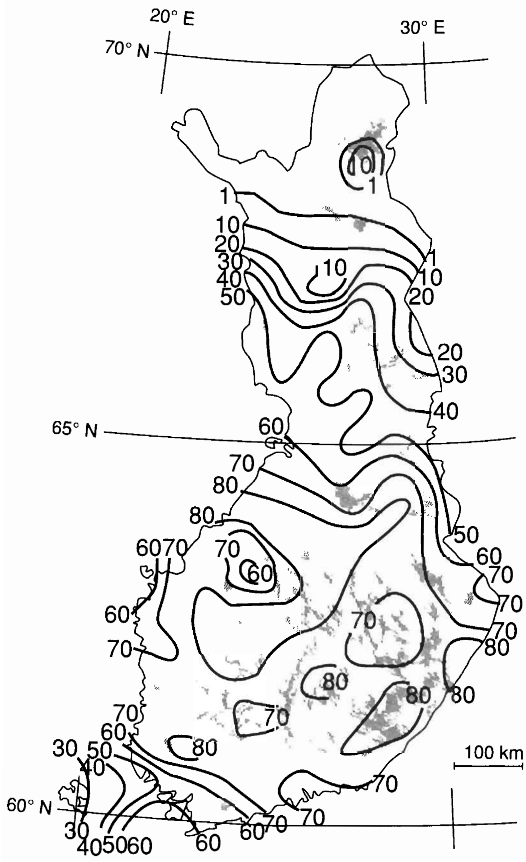

Chart 4. The proportion of drained mire area compared with the total mire area (%).

Kartta 4. Ojitettujen soiden osuus soiden kokonaisalasta (%).

matic effect for a 100% affecting area by the actual proportion of the affecting area.

METHOD

The climatic effects for a 100% affecting area

The climatic effects for a 100% affecting area, denoted by e, have been given by Solantie (1994, 1998) for all considered thermal variables except the mean monthly minimum temperature, which was calculated from the same material and by the same method as the others required for this study. Values of e were obtained by using observations from three neighbouring Finnish Meteorological Institute climatic stations within the middle boreal zone during the period 1959–1990. These stations (Chart 2), are Möksy (a) (63.1°N, 24.3°E, 171 m above sea level), Kauhava (b) (63.1°N, 23.0°E, 42 m a.s.l.) and Haapavesi (c) (64.1°N, 25.4°E, 123 m a.s.l.).

The proportion of drained mires compared with the total area, as well as the corresponding climatic effects, are very large in the surroundings of station a, but rather low at stations b and c. Station a, i.e. Möksy, was ideal as the main station for studying climatic impact of drainage for several reasons, making it possible to obtain results which are both reliable and generally applicable: (1) the proportion of drained mires is unusually high, (2) the proportion of drained mires is about the same, regardless of the radius of the encompassing circle considered, (3) there is a great variety of mire types in the surroundings, (4) the region is geographically in the heart of the middle boreal zone, (5) the draining timetable was unusually early (8 years in advance of the average), so that the end of the process can also be observed, (6) detailed data on individual mires and their drainage is available, and (7) the station has remained at exactly the same place during the period 1959–1990, and from 1996 onwards, with unchanged shielding in all compass directions.

The surroundings of all these stations (a, b, and c) are similar in respect to two main effects causing local variation in minimum temperatures; i.e. there are no large water bodies in the neighbourhood, neither are the stations located on a hill or in a valley. Further, no changes have occurred in the situation or shielding of any of the stations. Consequently, we may expect that the major factors affecting the differences in minimum temperatures between the stations are their heights above sea level and latitudes, and the drainage, only the last of which varies with time.

The climatic effects were calculated using regression models (Solantie 1994, 1998), in which the annual differences in the climatic variables between the weather stations were explained by the relative areas of the drained mires in the effecting stage around the stations, while the constant terms in the models (Solantie 1994, 1998) represent other climatic effects, such as those caused by the latitude and height above sea level which are mainly the same from year to year.

The thermal parameters involved and their values (i.e. the climatic effects) corresponding to a 100% affecting area were as follows:

1) The decrease in the daily (–4.8°C) and monthly (– 8.8°C) minimum temperatures during summer (May–Sept.) before canopy closure (i.e. less than 16 years from drainage).
2) The decrease in the duration of the frost-free period (98 days in the southern and middle boreal regions and 90 days in the northern boreal regions) before canopy closure.
3) The increase in daily minimum temperature (+2.7 °C) in winter (Nov.–March) and the increase in the yearly minimum temperature (+8.8 °C) after the canopy closure (compared with the periods of recently-drained and predrainage stages).

Formulae to obtain the climatic effects in grid-squares

The effect of drainage on climate was approximated as being proportional to the proportion of the drained mire area of the total area. During summer (1) and winter (2) we have

$$E = A_1 e \qquad (1),$$

and

$$E = A_2 e \qquad (2),$$

where E = the climatic effect considered, calculated as values in grid squares and prepared as isopleths charts, e = the climatic effect considered for a 100% affecting area, A_1 = the affecting area during summer (May–Sept.) in the considered year or period, and A_2 = the affecting area during winter (Nov.–March.) in the considered year or period.

Affecting areas and climatic effects in grid-squares for the periods considered

The effect of drainage on air temperature and involved thermal variables depends on the affecting area (A_1) which is different in the warm season and in winter. In winter the affecting area consists of all tree stands grown on drained mires, whereas in summer it consists of bare drained mires or those having small stands only. Consequently, the affecting area in the warm season (A_1) was defined as the drained area younger than 16 years old plus all unsuccessfully drained areas with small poorly-recovered stands only, whereas the affecting area in winter (A_2) was defined as the successfully drained area older than 15 years (more precisely below).

Periods during which nights are strongly cooled comprise the “recently-drained” stage and the beginning of the “transforming” stage. Using the results of successive forest inventories, the total amount of “recently-drained” mires in Finland is obtained. Correspondingly, the total annual amount of mire areas drained each year is also compiled. Summing annual amounts of new drainage backwards in time from the mean year of any NFI (Aarne 1994, p. 109), we can discover how many years are needed to accumulate the amount of “recently-drained mires” observed in the NFI considered. The mean result for the 7th and 8th inventories (Aarne 1992: 4 , Aarne, 1994: 57) is 12 years. The use of 15 years as the mean duration of the cooling stage thus falls at the beginning of the transforming stage; actually, the main period of the decreasing cooling effect lasts approximately 10 years, starting about ten years later and ending about 20 years later than the time at which those measures were taken.

Affecting areas in the warm season and winter change differently from year to year during a long term period, each of them having different values in each region and year.

A detailed regional analysis of the proportions of different kinds of drainage areas was made for this study in 1998 by the Finnish Forest Research Institute from the data of NFI 8 (1983–1993), approximately for the year 1988. The values were given as areal means in grid-squares of 50 km × 50 km = 2 500 km^2. The gridded variable needed for calculation of the affecting areas in the warm season was the proportion of drained mires in 1988 compared with the total area (land and inland waters), denoted by A_1^* (Chart 5), and in winter the corresponding proportion of successfully drained areas, denoted by A_2^* (Chart 6). The annual development of affecting areas was derived from the data of NFI by assuming that the proportion of affecting area of A_1^* or A_2^* has the same value (i.e. that of the average over Finland) in all grid-squares, but is changing annually.

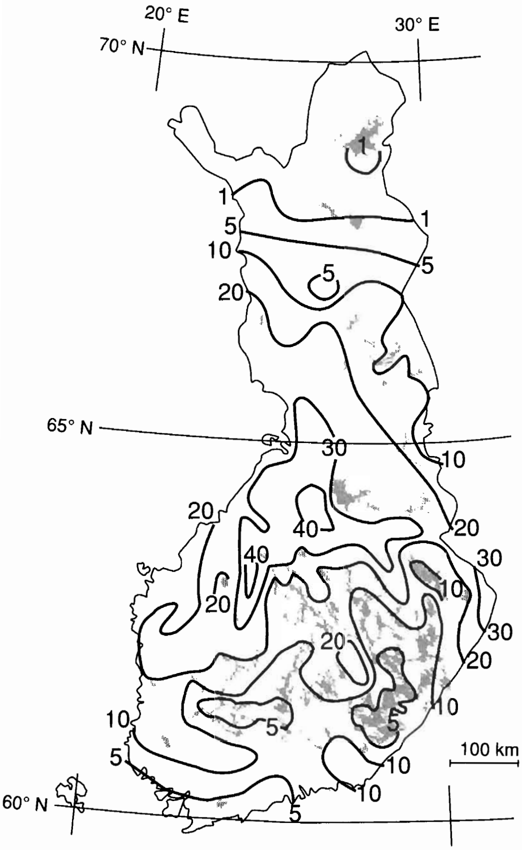

Chart 5. The proportion of drained peatlands (%) of the total area (incl. inland water areas) according to NFI 8.

Kartta 5. Ojitettujen soiden osuus (%) koko pinta-alasta (sisävesistöt ml.) VMI 8: n mukaan.

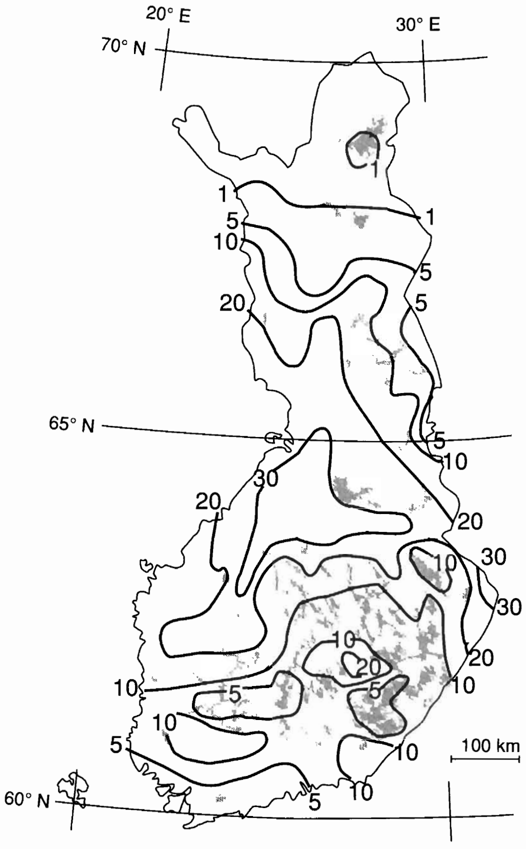

Chart 6. The proportion of the drained peatlands (%) with successful afforestation of the total area (incl. inland water areas) according to NFI 8.

Kartta 6. Onnistuneesti ojitettujen soiden osuus (%) koko pinta-alasta (sisävesistöt ml.) VMI 8:n mukaan.

This method is accurate enough, because the timetable for carrying out the drainage was very similar in various parts of the country, and areal variations in the drainage rate in the early 1970's were mostly local rather than regional (Salminen 1981). This means that the averages for Finland as a whole could be used for the proportions of affecting areas of A_I^* and A_2^* during the periods considered.

Some of the thin-peated mires in the "transformed" stage may continue to transform into "drained forests", which are no longer included in peatlands in national forest inventories. Such thin-peated mires, generally located at the edges of large mire complexes, also have shielding trees in their natural stage, so that the climatic changes caused by drainage remain small. In this study they are therefore excluded from "mires" (Chart 5); this occurred automatically, because the values of A_I^* and A_2^* were obtained from the results of the latest NFI (NFI 8), at the time till which practically all such changes had already occurred.

The charts showing the effects of drainage in summer were made for the 10-year period of the greatest impact, i.e. the period when the proportion of the mires which had been drained less than 16 years earlier was at its highest. This period was 1973–1982, when ca. 63% of drained mires were in that stage (i.e. $A_I = 0.63 \cdot A_I^*$).

The corresponding charts for winter are made for a time when almost all successfully drained mires are older than 15 years. This stage will be practically completed by the year 2005, and is now already very close to completion, i.e. the proportion is consequently 100% (i.e. $A_2 = A_2^*$). Thus, the areal effects for both summer and winter were calculated as follows.

For the effect on the mean daily minimum temperatures, denoted by E(m (°C))

$$E(m) = 0.63 \cdot A^*_1 \cdot (-4.8\ (°C)) = -3.0 \cdot A^*_1\ (°C) \quad (3).$$

For the effect on the mean monthly minimum temperatures, denoted by E (M (°C)):

$$E\ (M) = 0.63 \cdot A^*_1 \cdot (-8.8\ (°C)) = -5.5 \cdot A^*_1\ (°C) \quad (4).$$

For the duration of the period without temperatures below 0°C at a height of 2 m, denoted by E (D (days)), in the regions S, Sm, and M (Chart 2):

$$E\ (D) = 0.63 \cdot A^*_1 \cdot (-98\ (\text{days})) = -62 \cdot A^*_1\ (\text{days}) \quad (5a).$$

and in the regions Mn, N, and Nn (Chart 2)

$$E\ (D) = 0.63 \cdot A^*_1 \cdot (-90\ (\text{days})) = -57 \cdot A^*_1\ (\text{days}) \quad (5b).$$

For the effect on the mean daily minimum temperatures during winter, denoted by E (n (°C)), we obtain:

$$E\ (n) = 1.0 \cdot A^*_2 \cdot (+2.7\ (°C)) = +2.7 \cdot A^*_2\ (°C) \quad (6),$$

and for the annual minimum temperatures, denoted by E (N) (°C):

$$E\ (N) = 1.0 \cdot A^*_2 \cdot (+8.8\ (°C)) = +8.8 \cdot A^*_2\ (°C) \quad (7).$$

Chart presentation

Both the basic data of the drainage and its various stages, as well the results as climatic effects of drainage, were presented on charts prepared by the same method. All values were first presented as areal means in square areas of 2500 km^2; isopleth analyses were then made on the basis of these preliminary charts with square values. The isopleths on the charts were drawn by interpolating between values at the centres of neighbouring grid-squares, also taking the spatial second derivatives into account. In the vicinity of the specific research area at Möksy (in the municipality of Alajärvi. Chart 2), isopleths could be drawn more accurately than on the basis of grid-square values, without however any disagreement with the latter.

The square area of 2500 km^2 used is the smallest one for which reliable results for A^* can be obtained. Using a grid-square size of 2500 km^2, the standard error in the proportion of the specified mire type of the total area is about 3 percentage units (Hirvelä et al., 1998: 311, 312). The relative error in the climatologically affecting area is about 0.1, and the relative errors of the climatic effects in the middle boreal zone are also about 0.1. The accuracy of the grid-square data of drainage and the climatic effects of drainage are therefore accurate enough.

RESULTS

The climatic effects on the thermal variables during the warm season for the period 1973–1982 according to Equations (3) to (5) are shown in Charts 7 to 9, and the corresponding effects in winter from the year 2005 onwards according to Equations (6) and (7) in Charts 10 and 11. The corresponding regional means are given in Table 2. The related affecting areas in winter are the same as the proportions of successfully drained mires in Table 1 and Chart 6, while during the warm season they are the proportions of drained mires in Table 1 and Chart 5 multiplied by 0.63. The regions used in Tables 1 and 2 were the southern, middle and northern boreal zones, the boundary belts between these three zones being separated as regions of their own. These tables should be examined in connection with Chart 1, showing the main forest vegetation zones of Finland with boundaries from Kalela (1961), and Chart 2, showing the boundary belts between the zones, and the grid-square system of the basic data of draining. The boundary belts between the middle and northern boreal zones and between the middle and southern boreal zones in Chart 2 consist of those grid-squares through which the boundaries pass; the northern subzone of the northern boreal zone (Kalela's Metsä-Lappi) is here separated as the northern boundary belt of the northern boreal zone, and denoted Nn.

It can readily be seen that the natural regions (Charts 1 and 2) indeed form distinct patterns with respect to the proportion of drained mires compared with the total area: the proportion is greatest in the middle boreal zone (M), and decreases

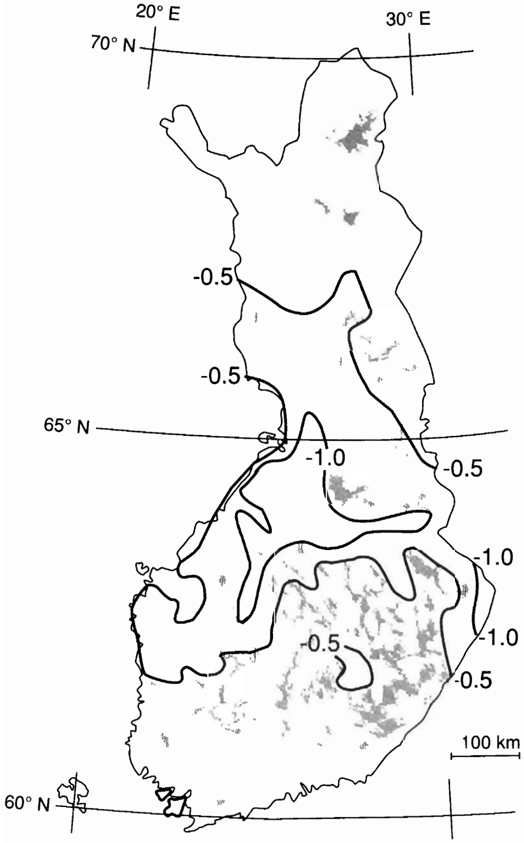

Chart 7. The effect over the total area (incl. inland water areas) of the drainage of mires without canopy closure on the mean daily minimum temperatures at the 2 m level in the period May–September during the ten years of maximal influence (1973–1982, °C).

Kartta 7. Puuttomien tai vähäpuustoisten ojitettujen soiden vaikutus vuorokauden keskimääräiseen minimilämpötilaan 2 metrin korkeudella touko–syyskuussa suurimman vaikutuksen kymmenvuotisjaksona koko pinta-alalla (sisävesistöt ml.) (1973–1982, °C).

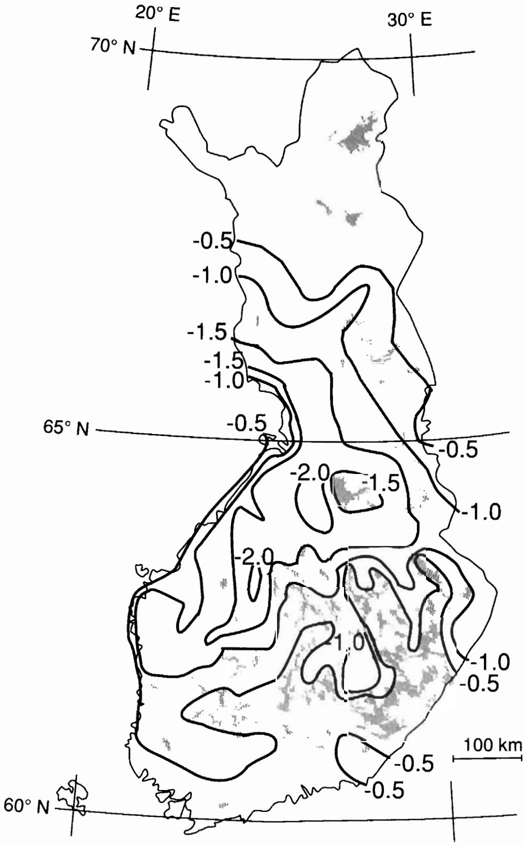

Chart 8. The effect over the total area (incl.inland water areas) of the drainage of mires without canopy closure on the mean monthly minimum temperatures in the period May–September at the 2m level during the ten years of maximal influence (1973–1982, °C).

Kartta 8. Puuttomien tai vähäpuustoisten ojitettujen soiden vaikutus kuukauden keskimääräiseen minimilämpötilaan 2metrin korkeudella touko–syyskuussa suurimman vaikutuksen kymmenvuotisjaksona koko pinta-alalla (sisävesistöt ml.) (1973–1982, °C).

both northwards and southwards. This fact is due to two main reasons. First, mires are more common in the middle and northern boreal zones (M and N) than in the southern boreal, for climatic reasons (Solantie 1974, 1986). Secondly, the drainage proportion of peatlands (= the proportion of the drained mire area compared with the total mire area (%)) is essentially greater in the southern and middle boreal zones than in the northern boreal, because of the corresponding difference in the economical profitability of drainage. Further, the proportion of successfully drained mire area compared with the total drained mire area decreases northwards, particularly at the northern limit of region M (Table 1), so that the warming effect in winter, albeit being greater than the cooling effect during the warm season throughout Finland, approaches the latter as one goes northwards.

In the middle boreal zone the effects of drainage can be described as regional but in the other zones as local. The effect of drainage on the mean daily minimum temperature in summer during the period 1973–1982 (maximum effect) averaged

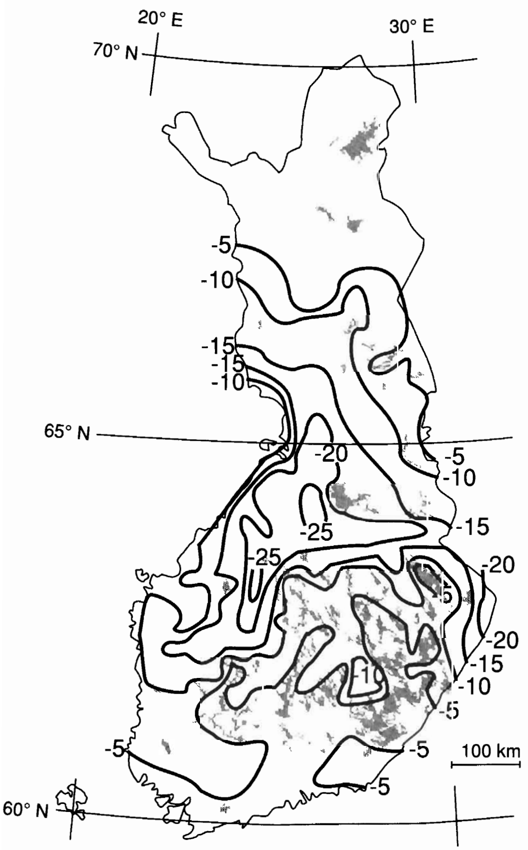

Chart 9. The effect over the total area (incl. inland water areas) of the drainage of mires without canopy closure on the length of the period without temperatures below 0°C at the 2m level during the ten years of maximal influence (1973–1982, days).

Kartta 9. Puuttomien tai vähäpuustoisten ojitettujen soiden vaikutus pakkasettoman kauden pituuteen 2 metrin korkeudella touko–syyskuussa suurimman vaikutuksen kymmenvuotisjaksona koko pinta-alalla (sisävesistöt ml.) (1973–1982, vrk).

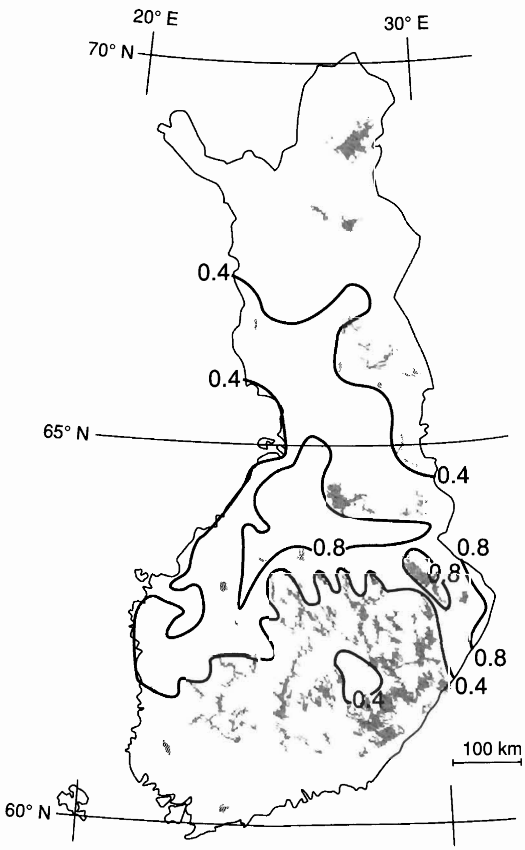

Chart 10. The permanent effect over the total area (incl. inland water areas) of the afforestation of drained mires on the mean daily minimum temperatures at the 2 m level during the period November to March (°C) from about the year 2005 onwards.

Kartta 10. Ojitettujen soiden metsittymisen pysyvä vaikutus vuorokauden keskimääräiseen minimilämpötilaan 2 metrin korkeudella marras–maaliskuussa koko pinta-alalla (sisävesistöt ml.) noin vuodesta 2005 eteenpäin (°C).

over the middle boreal zone (M) was – 0.8°C, whereas the corresponding averages over the northern (N) and southern (S) boreal zones were both only – 0.2°C, the change from the upper level (M) to the lower levels (N, S) occurring over the corresponding boundary belts between the zones (Mn and Sm) having values about half-way between (Table 2). A similar regional structure is valid both for the monthly minimum temperatures for the same period, the upper-level average (M) being – 1.5°C and the lower level averages – 0.4°C (N, S), as well as for the duration of the frost-free period, the corresponding values being – 17 days (M) and – 3.5 days (N, S) (Table 2).

This similar regional structure is valid for the effect of drainage on the daily and annual minimum temperatures in winter from the year 2005 onwards, the upper-level average in region M for the effect on mean daily minimum being + 0.7°C and that for the annual minimum + 2.2°C, while for the lower level averages (regions N and S) the effect on mean daily minimum and the effect on

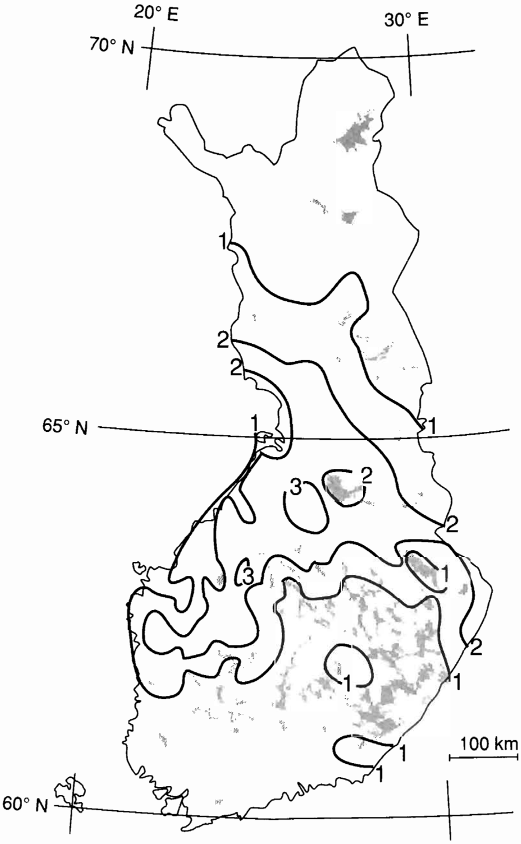

Chart. 11. The permanent effect over the total area (incl. inland water areas) of the afforestation of drained mires on the annual minimum temperatures at the 2 m level from about the year 2005 onwards (°C).

Kartta 11. Ojitettujen soiden metsittymisen pysyvä vaikutus vuoden minimilämpötilaan 2 metrin korkeudella koko pinta-alalla (sisävesistöt ml.) noin vuodesta 2005 eteenpäin (°C).

annual minimum were about + 0.2°C and + 0.6°C, respectively.

In the middle boreal zone, for each climatic effect, all grid values range between 0.71 and 1.48 times the average over the zone, thus being rather evenly distributed in space.

DISCUSSION

Part of the drained mires already had a moderate canopy closure before drainage. In contrast, a major part of the climatic effects due to drainage as observed at Möksy (Solantie 1994, 98) were caused by mires which were initially treeless or sparsely treed, and thus only insignificantly sheltered. Let us study the proportion of such mires in various part of Finland, and in the surroundings of Möksy. We have statistics of the development of stands on drained mires from 1930 to 1990, in which Finland is divided into five regions which are different from those used here (Ilvessalo 1957, Keltikangas et al. 1986, Minkkinen 1999, personal communication). In Finland as a whole, 62.0% of drained mires were initially practically unsheltered. In the five subregions, the values ranged from 54 to 66%.

Thriving spruce mires, which cover 19.5% of the drained area of Finland and over 10% in each subregion, are the largest class of drained mires which initially have a good canopy closure. In some parts of the middle boreal zone, such mires are, however, very uncommon, and also the proportion of drained areas with a good canopy closure occur less there than generally. Such barren regions have common characteristic features, as follows:

1) Spruce mires comprise less than 10% of the mire area (Ilvessalo 1960).
2) Sites of grass-herb and dwarfshrub-grass-herb types comprise less than 10% of the forestry land area (Ilvessalo 1960).
3) Mires comprise over 40% of the land area (Ilvessalo 1960), drained mires over 30% (Fig. 5).

These regions comprise 30% of the middle boreal zone and 9% of Finland, but 19% of Finnish drained mires. The station of Möksy is located within just such a barren region. The equations used to prepare the charts, basing on the observations and studies at Möksy, apply most exactly to just those regions, where the climatic effects are greatest and most significant. In the nearest neighbourhood of Möksy, i.e. in a station-centred circle with a radius of 1.0 km, there are 2.0 km^2 of drained mires. Of these drained mires, 80% were initially practically without shelter from stands, and additionally spruce mires comprised only 3% of the drained area (basic data: Finnish forest and park service, Karstula unit, unpub.). If we apply this 80% to 10% of the Finnish area, then initially treeless or sparsely treed mires comprise 60% of the area of drained mires in the rest of Finland. According to this, the effects of drainage can be directly obtained for the barren heart of the middle boreal zone (comprising 10% of Finland) from Equations (2) to (5), but for the rest of Finland the results obtained from these equations should be multiplied by 60/80 = 0.75, and for Finland as a whole by 62/80 = 0.77.

The effects given in the charts and tables thus seem to be somewhat too high, except in the area of maximal effects. The approximate errors in the climatic effects so calculated are as follows:

1) For mean daily minimum temperatures in summer: – 0.1°C.
2) For mean monthly minimum temperatures in summer: – 0.1 to – 0.2°C.
3) For duration of the frost-free period: – 1 to –2 days.
4) For mean daily minimum temperatures in winter: + 0.1°C.
5) For annual minimum temperatures: + 0.3°C.

In fact, the errors are smaller than the above figures. According to the statistics for Finland as a whole, the maximum of the curve showing the proportion of drained mires in the cooling stage in summer is flatter than locally; consequently, the highest ten-year-period mean is actually higher in any single grid-square than for Finland as a whole. If we very realistically suppose that the ten-year maximum in single grid-squares is typically 80% instead of the average (62.5%), the overestimation is eliminated. In any case, any possible slight overestimation of the climatic effects does not occur in regions where the effects are most significant.

The draining of mires has a particularly strong impact on the duration of the frost-free period. The last frosts in spring and the first frosts in autumn occur so close to the peak of the sine curve of the annual course of the mean daily minimum temperatures that the mean daily change there is small; consequently, even slight effects on minimum temperatures cause rather large changes in the duration of the frost-free period. The response of the change in the duration of this period to the change of the mean minimum temperature is greatest in the watershed regions of the middle boreal zone, where the proportion of drained mires is highest, albeit for simplicity the same value of this response in Equation (5a) was used throughout the southern and middle boreal zones. In the

Table 1. Regional means of drainage data (for regions, see Chart 1).

Taulukko 1. Ojitustietojen alueellisia keskiarvoja (alueet Kartassa 1).

Region — *Alue*	A (%)	B (%)	C (%)	D (%)
S	7.8	7.6	72.5	3
Sm	15.2	14.3	74.6	6
M	27.2	24.5	71.7	10
Mn	20.9	17.0	50.6	18
N	7.2	5.7	19.7	20
Nn	0	0	0	–

A = the proportion of drained mires compared with the total area (incl. inland waters); B = the proportion of successfully drained mires compared with the total area (incl. inland waters); C = the proportion of drained mires in 1988 compared with the total mire area in 1988, D = the proportion of unsuccessfully drained mires compared with the drained mire area.

A = ojitetun suon osuus kokonaispinta-alasta (sisävesistöt ml.); B = onnistuneesti ojitetun suon osuus kokonaispinta-alasta (sisävesistöt ml.); C = ojitetun suon (1988) osuus koko suoalasta (1988); D = onnistuneesti ojitetun suon (1988) osuus koko suoalasta (1988).

Table 2. Regional means of climatic effects in winter after the year 2005, and in summer during the 10 years of greatest effect (1973–1982); for Regions, see Chart 1.

Taulukko 2. Ilmastovaikutusten alueellisia keskiarvoja, talvella vuodesta 2005 eteenpäin, kesällä 10 suurimman vaikutuksen vuotena (1973–1982); alueet Kartassa 1.

Region *Alue*	A (°C)	B (°C)	C (°C)	D (°C)	E (days — *vrk*)
S	+ 0.2	+ 0.7	– 0.2	– 0.4	– 3
Sm	+ 0.4	+ 1.3	– 0.5	– 0.8	– 9
M	+ 0.7	+ 2.2	– 0.8	– 1.5	– 17
Mn	+ 0.5	+ 1.5	– 0.6	– 1.1	– 12
N	+ 0.2	+ 0.5	– 0.2	– 0.4	– 4
Nn	0	0	0	0	0

A = daily minimum temperature in winter; B = annual minimum temperature; C = daily minimum temperature in summer; D = monthly minimum temperature in summer; E= duration of the frostless period.

A = vrk: n minimilämpötila talvella; B = vuoden minimilämpötila; C = vrk :n minimilämpötila kesällä; D = kuukauden minimilämpötila kesällä; E = pakkasettoman kauden pituus.

northern boreal zone, where the summer maximum in the seasonal course of the mean minimum temperature is rather sharp, the duration of the frostless period is less sensitive to changes in the mean level of minimum temperatures caused by drainage; a smaller value of e was therefore used there (Equation (5b)).

The effects of drainage and the related stages of forest development and their changes in time, based mainly on climatic time series from the station of Möksy having surroundings of which 55% is covered by drained mires of various kinds typical of the barren heart of the middle boreal zone, agree well with the physical background. There also exists other evidence supporting the result, e.g. model simulations of the lower troposphere during conditions of clear sky, calm weather and dry underlying peat (Venäläinen et al. 1999). Other support arises from the fact that in the period 1931–1960 the May–Sept. mean temperatures in the middle boreal zone of Finland were only 0.02°C lower than those of the corresponding area in Sweden, whereas in the period 1961–1990 the Finnish values were 0.10°C lower than the Swedish (Solantie 1993). Consequently, in the middle boreal zone (with widespread draining during the latter period in Finland), the change in mean temperature in Finland between the period 1931–1960 and the period 1961–1990 was 0.08°C more than that in Sweden, whereas in both the northern and southern boreal zones the corresponding difference was only 0.02°C. On the other hand, the effect of draining on the May–Sept. mean temperature in the middle boreal zone during the period 1961–1990 is – 0.11°C and – 0.03°C in the southern and northern boreal zones, respectively, i.e. of the same order as the above differences between Finland and Sweden; this result is obtained by applying Equation (3) and by approximating the affecting area around the stations as being a half of the actual.

In region M, the standard deviation of the ten-year means of the seasonal means of daily minimum temperatures during the warm season is of the order of 0.5°C (Solantie 1999) and that of the duration of the period without temperatures below 0°C at a height of 2 m of order of 12 days (Solantie 1998). Thus, in region M the highest ten-year average effects of drainage on these variables are about 1.5 times the standard deviation of the ten-year averages. Consequently, the average magnitudes of the cooling effects caused by drainage in the middle boreal zone (Table 2, Charts7 to 9) are equal to deviations from the climatic basic means which occur in natural conditions in one of the 10 to 15 successive ten-year periods. However, in the regions of the main watersheds, comprising about 20 000 km^2, these drainage effects are more than 1/3 higher, and equal to deviations from the climatic basic means occurring in natural conditions with return periods of several hundred years. In the southern and northern boreal zones, the climatic effects of drainage are comparable to natural variations that are quite common. After the hardest ten-year period during the warm season, the cooling effects have considerably decreased with the development of stands on drained areas, while the warming effects in winter have risen to close to their permanent levels (Charts 10 and 11).

The regional features of the effects of the drainage on climate are mainly accentuated by other forestry methods. Young stands and open areas in forests, caused by logging, also lack the shelter provided by trees, thus being cold during summer nights. The regional features of the proportion of such forests during the period of the greatest effect of drainage was very similar to that of drained mires: in the southern boreal zone the proportion was about 20% and in the middle boreal zone about 40% (Salminen 1973), so that the regional distribution of the total effect of forestry measures is very similar to that of drainage. However, the main isopleth of 30% crosses the boundary between the middle and southern boreal zones obliquely, so that in the west the area where the proportion of such forests was less than 30% extended north of the boundary, whereas in the middle and east the area with values over 30% extended south of the boundary (Chart 3) into the region Sm (Chart 2). In this region also the proportion of drained mire area compared with the total mire area (%) is particularly high, exceeding 80% over wide areas (Chart 4); the most barren mires of all, on which stands cannot become closed, and which may even become permanently colder than before draining, also comprise here as much as 20% of drained mires (Keltikangas et. al. 1989), whereas the average over Finland is 13%. These factors extend the middle boreal climate southwards, so that the climatic boundary belt between the southern and middle boreal zones slips southwards and sharpens, which Solantie (1998) has verified by climatic observations. The genotype of trees in this boundary belt obviously comprises many southern boreal elements, making these forests vulnerable under adverse climatic changes such as those caused by simultaneous drainage and massive loggings.

Mires in the middle boreal zone also have a natural lowering effect on minimum temperatures, which can be seen in the Swedish middle boreal series (Solantie 1992). It may thus be possible that this natural effect accounts for part of the effect of drainage, and that the latter effect is somewhat overestimated. In spite of this, the regional features in the charts are correct, because the proportion of drained mires is about 70% in all regions of the southern and middle boreal zone. Further, the portion of the cooling effect in summer which remains permanent over 50 years after the draining is not yet very accurately determined. In any case, the most important result, to show the magnitude and regional features of the total climatic effects of the mires in the middle boreal zone in the form of charts, is useful for forestry, ecology and climatology. In order to recognise the global climate change in Finland, it is important to distinguish between the natural effects of mires, the effect of drainage and the global change, of which the latter two have long trends. The maintenance of and research on temperature series of long duration are therefore particularly important, especially in the middle boreal zone. It is an appropriate time to continue research by studying the development of forest vegetation during the period 1951–2010 in the middle boreal zone and particularly in its most affected part.

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REFERENCES

Aarne, M. 1992 (edit.). Yearbook of Forest statistics 1990–1991. Folia Forestalia 790: 1–281.

Aarne, M. 1994 (edit.). Yearbook of Forest statistics 1993–94. The Finnish forest research Institute 1994 (Helsinki): 1–281.

Hirvelä, H., Nuutinen, T. & Salminen O. 1998. Valtakunnan metsien 9. Inventointiin perustuvat hakkuumahdollisuusarviot vuosille 1997–2026. Etelä–Pohjanmaan Metsäkeskuksen alueella. Metsätieteen aikakauskirja 2B/98: 1–374.

Ilvessalo, Y. 1956. Suomen metsät vuosista 1921–1924 vuosiin 1951–1953. (Summary: The forests of Finland from 1921–1924 to 1951–1953. A survey based on three national forest inventories). Communicationes Instituti Forestalis Fenniae 47: 1–227.

Ilvessalo, Y. 1957. Suomen metsät metsänhoitolautakuntien toiminta-alueittain. Valtakunnan metsien inventoinnin tuloksia. (Summary: The forests of Finland by forestry board districts). Communicationes Instituti Forestalis Fenniae 47: 1–128.

Ilvessalo, Y. 1960. Suomen metsät kartakkeiden valossa. (Summary: the forests of Finland in the light of maps). Communicationes Instituti Forestalis Fenniae 52: 1–70.

Kalela, A. 1961. Waldvegetationszonen und ihre klimatischen Paralleltypen. Arch. Soc. "Vanamo", 16: suppl. 1961: 65–83.

Keltikangas, M., Laine, J., Puttonen, P & Seppälä, K. 1986. Vuosina 1930–1978 metsäojitetut suot: ojitusalueiden inventoinnin tuloksia. (Summary: Peatlands drained for forestry during 1930–1978: results from the field surveys of drained areas). Acta Forestalia Fennica 193: 1–94.

Salminen, S. 1973. Tulosten luotettavuus ja karttatulostus valtakunnan metsien V inventoinnissa. (Summary: Reliability of the results from the fifth national forest inventory and presentation of an output mapping technique). Communicationes Instituti Forestalis Fenniae 78.6: 1–64.

Salminen, S. 1981. A cartographic presentation of forest resources in Finland 1971–1975. Folia Forestalia 483: 1–42.

Solantie, R. 1974. Kesän vesitaseen vaikutus metsä- ja suokasvillisuuteen ja linnustoon sekä lämpöolojen välityksellä maatalouden toimintaedellytyksiin Suomessa. (Summary: The influence of water balance in summer on forest and peatland vegetation and bird fauna and through the temperature on agricultural conditions in Finland). Silva Fennica 8: 160–184.

Solantie, R. 1986. Suoyhdistymätyypeistä suhteessa ilmastollisiin ja hydrologisiin vyöhykkeisiin. (Summary: The zonation of peatland complex types in relation to climatic and hydrological zones). Suo 37: 73–86.

Solantie, R. 1992. Counterparts of Finnish climate zones in Sweden. Meteorologisia julkaisuja–Meteorological publications 21: 1–54.

Solantie, R. 1993. The change in the thermal climate between the periods 1931–1960 and 1961–1990, in relation to the natural zones in Fennoscandia. (In Finnish with English abstract). Meteorologisia julkaisuja–Meteorological publications 25: 1–16.

Solantie, R. 1994. The influence of large-scale draining of peatlands on air temperature, with special reference to observations at Alajärvi, central Finland. (In Finnish with English abstract). Meteorologisia julkaisuja–Meteorological publications 29: 1–40.

Solantie, R. 1998. The influence of large-scale drainage of peatlands on the duration of the frostless period and annual temperature minima 1961–1990 and on temperature trends since 1990. (In Finnish with English abstract). Meteorologisia julkaisuja–Meteorological publications 38: 1–43.

Solantie, R. 1999. Temperature conditions during the periods 1931–1960 and 1961–1990 compared with the long term climatic mean. (In Finnish with English abstract). Meteorologisia julkaisuja–Meteorological publications 39: 1–39.

Valtakunnan metsien 8. Inventointi. Kenttätyön ohjeet. Pohjois–Karjalan versio. Metsänarviomisen tutkimusosasto, metsäninventoinnin tutkimussuunta. Helsinki 1989, 97 pp.

Venäläinen, A., Rontu, L. & Solantie, R. 1999. On the influence of peatland draining on local climate. Boreal Environment Research 4: 89–100.

TIIVISTELMÄ:

Karttoja suo-ojitusten vaikutuksesta Suomen ilmastoon

Suomen soiden suurimittainen ojitus, joka tehtiin 1950–1990, vaikutti ilmastoon monella tavoin. Nämä vaikutukset ovat niin merkittäviä (Solantie (1994, 1998)), että karttojen laatiminen niistä on aiheellista. Tämän tutkimuksen tarkoituksena on yhdistää tietous suo-ojituksista ja niiden ilmastovaikutuksista kartastoksi. Vaikutukset on jaettavissa lämpimän vuodenajan vaikutuksiin, jotka ovat väistyviä, ja talvivaikutuksiin, jotka ovat pysyviä.

Lämpimänä vuodenaikana ojituksen jälkeen kuivunut pintaturve toimii eristeenä, joka estää lämmönvaihdon syvemmällä olevan turpeen ja ilman välillä. Ojitettujen soiden metsityttyä eli noin 15 vuotta ojituksen jälkeen on pahin kylmäämisvaikutus ohi; vain epäonnistuneet ojitukset jäävät hallanpesiksi. Soiden metsittyminen lauhduttaa pysyvästi myös talvipakkasia inversio- ja ulossäteilytilanteissa; erityisesti lämpötilan vuosiminimit nousevat. Metsittymisen lauhduttava vaikutus inversiotilanteissa johtuu siitä, että pääasiallisin ulossäteilypinta siirtyy metsityksen myötä maanpinnasta latvustasolle, jolloin säteilyjäähtyminen latvustason alapuolella vähenee. Lisäksi latvustasolla jäähtyvän ilman vaipuessa ja latvustason ilman sekoittuessa heikonkin tuulen vaikutuksesta, sekoittuu alin ilmakerros metsittymisen vaikutuksesta tehokkaammin, niin että inversio heikkenee ja maanpinnan läheinen ilmakerros lämpenee.

Karttojen laatiminen kävi mahdolliseksi vasta 1998, kun Metsäntutkimuslaitos (Erkki Tomppo, Kari Korhonen) analysoi tekijän toivomuksesta ojituksia kuvaavan aineiston ensi kerran metsäkeskuksia tarkemmalla alueellisella erottelukyvyllä vuosina 1983–1993 suoritetun valtakunnan metsien 8. inventoinnin (VMI 8) tuloksista. Koealojen rajoitetun määrän takia pienin alueyksikkö, jolle tulokset ovat tilastollisesti riittävän luotettavia, on 2500 km^2 (E. Tompon arvio). Siten ojituksen vaikutuksia tarkasteltiin 50 km x 50 km:n ruuduissa. Ruutuarvojen pohjalta laadittiin kartat, joissa on esitetty metsäojitettujen soiden osuus soiden kokonaisalasta (pl. kankaiksi muuttuneet suo-ojikot) (Kartta 4), ojitettujen soiden osuus kokonaisalasta (sisävesialueet ml) (Kartta 5) ja vastaava kartta niille ojitetuille soille, joissa metsittyminen oli onnistunut (Kartta 6). Nämä perusdatat on esitetty myös metsäkasvillisuusvyöhykkeittäin (Taulukko 1).

Ojitusten vaikutuksia ilmastoon koko maa-alalla kuvattiin kahtena karttasarjana, joista toinen kuvaa kuivumisvaiheessa olevien ojikkojen jäähdytysvaikutusta lämpötilan keskimääräiseen vuorokausiminimiin ja kuukausiminimiin sekä pakkasettoman kauden pituuteen kesällä (touko–syyskuussa) suurimman vaikutuksen kymmenvuotiskautena 1973–1982 (Kartat 7–9). Toisessa karttasarjassa (Kartat 10 ja 11) esitetään ojitettujen soiden latvuston sulkeutumisen aiheuttamat pysyvät lämmitysvaikutukset lämpötilan vuosiminimiin ja keskimääräiseen kuukausiminimiin talvella (marras–maaliskuussa) siinä vaiheessa, kun suunnilleen kaikki onnistuneesti ojitetut suot ovat metsittyneet eli noin vuonna 2005, verrattuna latvustason sulkeutumista edeltäneeseen kauteen sekä ennen ojitusta että sen jälkeen.

Ilmastovaikutukset koko maa-alalla laskettiin 50 km × 50 km:n ruutujen aluearvoina kahden parametrin tulona; ruutuarvojen perusteella laadittiin sitten tuloskartat, joissa vaikutuksia kuvataan samanarvonkäyrinä. Nämä kaksi parametria ovat (1) ojitusten vaikutus (e) tarkasteltavaan ilmastomuuttujaan tapauksessa, jossa ilmastollisesti vaikuttavan ojikkovaiheen osuus koko pinta-alasta (sisävesialueet ml.) on 100 % ja (2) parametri (A_i, kesällä A_1, talvella A_2), joka ilmoittaa kussakin km × 50 km:n ruudussa, kuinka suuri osa kokonaispinta-alasta (maa- ja sisävesialueet ml.) on tarkasteltavana aikana sellaisessa metsäojitusvaiheessa, joka vaikuttaa ilmastoon.

Ojituksen ilmastovaikutukset (e, °C) ovat keskimääräiselle vuorokausiminimille talvella (marras–maaliskuussa) 2,7; lämpötilan vuosiminimille 8,8; keskimääräiselle vuorokausiminimille touko–syyskuussa – 4,8 ja keskimääräiselle kuukausiminimille touko–syyskuussa –8,8; viimeksi mainittu arvo laskettiin erikseen tässä tutkimuksessa samalla tavoin kuin muutkin kolme aikaisemmin. Solantie (1998) on laskenut vielä vastaavan kertoimen pakkasettoman kauden pituudelle (vrk) 2metrin korkeudella; tulos vaihteli hieman alueittain, ollen pohjoisboreaalisessa vyöhykkeessä -90 ja muualla keskimäärin -98.

Ilmastoon vaikuttavassa ojitusvaiheessa kauden 1973–1982 kesinä oli Suomessa keskimäärin 63% metsäojitetun suon määrästä v. 1988, kun taas talvella v. 2005 ja siitä eteenpäin tällaisessa vaiheessa ovat kaikki vuoteen 1988 mennessä onnistuneesti ojitetut suot. Siten $A_1 = 0{,}63\, A^*_1$, missä A^*_1 on metsäojitusten osuus koko pinta-alasta (sisävesialueet ml.) 50 km × 50 km:n ruuduissa valtakunnan metsien 8. inventoinnin (VMI 8) mukaan eli noin v. 1988; vastaavasti $A_2 = A^*_2$, missä A^*_2 on onnistuneiden metsäojitusten osuus v. 1988, laskettuna samalla tavoin ja samasta aineistosta kuin A^*_1.

Tulokset on esitetty kartoissa 7–11 ja Taulukossa 2. Niistä havaitaan, että ojitusten vaikutukset lämpöilmastoon ovat olleet merkittävät nimenomaan keskiboreaalisessa vyöhykkeessä (Kartat 1 ja 3). Etelämpänä soita on ilmastollisista syistä vähän. Pohjoisempana suot taas ovat ilmastollisista syistä yleensä ojituskelvottomia; tämä näkyy myös siitä, että keski- ja pohjoisboreaalisen vyöhykkeen rajaseuduilla, joissa soita ojitettiin paljonlaisesti, on epäonnistuneiden ojitusten osuus suuri (Taulukko 1). Erityisesti keski- ja eteläboreaalisten vyöhykkeiden rajaseudulla ojitusaste on erityisen suuri (Kartta 4); ojitusten vaikutusta ilmastoon ovat siellä vahvistaneet samanaikaiset rankat hakkuut (Kartta 3).

Karttoihin lasketut ilmastovaikutukset perustuvat pääosin Alajärven Möksyn havaintojen soveltamiseen laajempien alueiden ojitettuihin soihin. Möksyn ympäristössä niiden metsäojitettujen soiden osuus, joissa puusto oli verraten sulkeutunut jo ennen ojituksia, oli 20% (Metsähallituksen Karstulan hoitoalueen tiedostot), kun se Suomessa keskimäärin oli 37.5% (Keltikangas et al. 1986); siten Möksyn tulosten käyttäminen saattaa johtaa lievään ojitusten vaikutusten yliarviontiin. Kuitenkin Möksy ja sen tulokset edustavat parhaiten juuri sellaisia alueita, joilla ojitettuja soita on eniten ja niiden vaikutus ilmastoon on suurin; yhteistä tällaisille alueille on alunpitäen runsaspuustoisimpien soiden, korpien, hyvin pieni osuus suoalasta (esim. Ilvessalo 1960). Siten kartat ovat sitä tarkempia, mitä suurempi on metsäojitettujen soiden määrä ja niiden vaikutus.

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