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# Occurrence of Unfrozen Ground in Finland

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## *Abstract*

*In the area of the Fennoscandian inland climate, which is rather mild and rainy, the soil occasionally remains unfrozen under a deep snow cover. The frequency of such conditions varies strongly between regions. Sites providing soil temperature and soil frost observations are too few for a reliable regional analysis. Annual grid point charts of snow depth on March 15th for open fields and forests are, however, available; their analysis gives charts with a high spatial resolution corresponding to various percentage points in the temporal distribution of snow depths. Regression equations were derived, giving the frequency of unfrozen ground as a function of $P^{0.33}/D_6$ where P denotes the average frost sum, the exponent is empirical and $D_6$ is the snow depth on March 15th exceeded in 6 out of 100 winters, which is of the same order as the frequency of winters with unfrozen ground. Applying the resulting regression equations, charts with a high spatial resolution could be made for the frequency of unfrozen soil for open fields and forests. Good agreement was found with the distributions of several ecological and agricultural phenomena related to the occurrence of unfrozen ground.*


*Key words: Soil frost, unfrozen ground, forest ecology, wintering*

## *1. Introduction*

In the Fennoscandian inland climate with relatively mild winters and high precipitation, winters with unfrozen ground occur in most regions. Series of regular soil frost observations in Finland are few and are shorter than series of snow depth. On the other hand, lots of data are available from observations of the effective temperature sum (implying heat storage of the ground in autumn), the air temperature in winter and the snow depth, i.e. the three main climatic factors determining the spatial distribution of the probability of unfrozen ground. In a country like Finland with a small spatial variation in its continentality, the two thermal factors have approximately similar regional distributions, whereas snow conditions are much determined by the orographic effect on precipitation. Thus, an analysis of the probability of unfrozen ground throughout winter having a good spatial resolution could be carried out employing a function with frost sum and snow depth as independent variables, and constructing a chart of this probability by calculating grid point values from the emerging regression

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equation. On a regional scale, the frost sum increases smoothly from south-west to north-east whereas snow depth varies appreciably over short distances, and is the most significant factor affecting the frequency of unfrozen ground.

Unfrozen ground is characterized by a thick snow cover, falling in early winter and staying until spring. Furthermore, with few exceptions, a thick snow cover in March is possible only if a major part has already fallen at an early stage. For example, let us consider the 8 longest time series of the water equivalent of snow cover for basins south of the Arctic Circle in Finland (*Reuna et al.* 1993), namely the Vuoksi, Kymijoki, Vantaanjoki, Karjaanjoki, Kokemäenjoki, Kyrönjoki, Oulujoki and Iijoki basins, covering the major part of Finland south of the Arctic Circle. In each of these series, for 38 to 47 years including and previous to the year 1993, the three highest values measured on March 15$^{th}$ were considered, 24 altogether.

Of the values on January 15$^{th}$ preceding these 24 maxima on March 15$^{th}$, 20 exceeded the average in January by more than 50% and the rest were also higher than the average. Consequently, occurrence of thick snow packs on March 15th can be well related to the probability of unfrozen soil. By further using a chart of the long-period average of the frost sum by *Soveri and Varjo* (1977), a chart of the probability of unfrozen ground could be made as a function of snow depth and frost sum more accurately than if based on soil frost observations alone.

Frequent occurrence of unfrozen ground has significant consequences for the occurrence of snow mould fungi, injurious to wintering crops. Charts of the probability of unfrozen ground throughout winter would be highly useful for the planning of rye cultivation, which can be seen by studying charts of snow depths in connection with studies of the crop failure of rye. In the map analyses of annual rye yields for the period 1950—1975 (*Mukula et al.* 1976), hectare yields 20% below the average, which occurred in 1955, 1956 and 1962 over large areas, are the consequence of this harmful phenomena. In the statistics giving the proportion of the area of severe wintering damage for rye of the total area sown with rye in Finland 1968–1985 *(Samnordisk planteforedling (SNP)* (1988)), the wintering damage of 37% in 1981 and of 10% in 1984 are also due to the same cause. Further, charts of the probability of unfrozen ground throughout winter are useful for the choice and protection of perennials and biennials in gardening, and for understanding the distribution and winter hardiness of animal and plant species which overwinter under snow. Also, problems for forestry measures carried out by heavy machines in winter can be better foreseen. The wintering of rye also has connections with Finnish settlement history.

## 2. *Material*

Observations of soil frost depths using methyl blue tubes, read every ten days during the period 1968/1969–1989/1990, have been analysed by *Huttunen and Soveri* (1993); freezing of the soil is indicated by a change in colour (*Grandahl*, 1957). More than half of the observation series began in the winters of 1971/1972 (9 sites) or 1970/1971 (6 sites). Of the total material, the 25 series for agricultural fields and an equal number for forests south of the Arctic Circle, which extended over at least 14 winters, were considered sufficiently long. At each station, the maximum depth of soil frost during each winter was considered.

Data for snow depth on March 15$^{th}$, consisting of annual grid point values of snow depth with a grid size of 20x20 km over a period of 44 years (1919—1962), separately for open fields and forests, was available at the Finnish Meteorological Institute. The data allowed a good spatial resolution and continuous series in the part of Finland south of the Arctic Circle. The area of the region considered is 260 000 km$^2$. The mean number of people observing snow depth in this region annually on March 15$^{th}$ was about 1700. Consequently, at each grid point the snow depth was observed on average in 4 locations. On average, each observer measured the snow depth in 4 places, 1.5 in open fields and 2.5 in forests. Each grid value on the annual map for forests is therefore based on average of 10 snow depth sticks; the corresponding value in the case of open fields was 6. In order to eliminate the effect of hummocks and hollows, the measuring stick was pushed down into the snow on both sides and in front of the observer; of the three readings, the middle one was chosen.

Corresponding snow depths on March 15$^{th}$ at soil frost observation sites during winters of soil frost observations were also considered; this data is published in the Hydrological Yearbooks 1971–1990 (*National Board of Waters*, Finland 1975, 1976, 1977, 1980, 1981, 1983, 1987 and *National Board of Waters and the Environment* 1990, 1991, 1992, 1993).

The spatial distribution of the frost sum in the air does not vary much from one winter to another. Therefore, a chart presenting average values for the period 1955–1975 as isopleths, produced by *Soveri and Varjo* (1977), was used. Values for both snow depths 1919–1962 and the frost sum, also needed at the locations of the soil frost observation stations, were read from the respective charts.

## *3. Method*

Let us begin with the theory of soil frost formation from the theoretical point of view according to formulae by *Andersson* (1964). If snow has fallen on unfrozen ground, the formation of subsequent soil frost is prevented by the snow cover if

$$T > - g \cdot (k_1 / k_2) \cdot D_m \qquad (1)$$

where
$T$ = the mean temperature ($^{o}$C),
$g$ = the temperature gradient in the upper soil layer ($^{o}$C cm$^{-1}$),
$k_1$ = the heat conductivity of the upper soil layer (cal cm$^{-1}$ s$^{-1}$ $^{o}$C$^{-1}$)
$k_2$ = the heat conductivity of the snow cover (cal cm$^{-1}$ s$^{-1}$ $^{o}$C$^{-1}$) and

$D_m$ = the mean snow depth (cm).

Approximating $k_2$ by 0.003 cal $cm^{-1}$ $s^{-1}$ $^oC^{-1}$ and noting that values of $k_1$ vary between 0.00015 and 0.0017 (*Andersson*, p. 198), we found that $2.4 < k_1/k_2 < 27$. In south-western Finland, winter deepens slowly, and frequent thaw periods supply the snow cover with liquid water; because of the refreezing of this water, icy layers are formed in the snow, raising the value of $k_2$ .This is implied by the fact that the density of snow increases with the mean temperature. In relation to the mean density of the snow cover, we may approximate the value of $k_1/k_2$ in south-western Finland by 8 and in Lapland by 12. Considering further that g is about 0.02 ($^oC$ $cm^{-1}$), and that T, during the period from the beginning of thermal winter to March 15th, is in south-western Finland around -5 $^oC$ and on the Arctic Circle around -10 $^oC$, we obtain from Equation (1) that during this period the mean snow depth which can prevent soil frost formation in south-western Finland is $D_m > 31$ cm and on the Arctic Circle is $D_m > 41$ cm. Noting further that snow depths on March 15th, denoted by D, are greater than $D_m$, by a factor of about 1.5, unfrozen ground is expected in south-western Finland if D > 46 cm and on the Arctic Circle if D > 62 cm. The frequency of unfrozen ground throughout winter should be of the same order as the frequency of these snow depths.

The increase in the depth of soil frost per day is given by *Andersson* (1964) as

$$dx/dt = h \cdot (- T/(x + (k_1/k_2) \cdot D_m) - g) \tag{2}$$

x = the depth of soil frost, and
$h = 1.25 \cdot (k_1/w)$ $cm^2 s^{-1}$ $^oC^{-1}$
where $k_1$ = the heat conductivity in the ground and w (%)= the volumetric water content in the ground. For the other symbols, see Equation (1).

Integrating equation (2) according to *Andersson* (1964), and neglecting some small terms, we obtain

$$x_e = (2 \cdot h \cdot P_d + ((k_1/k_2) \cdot D_m)^2)^{0.5} - (k_1/k_2) \cdot D_m - 0.5 \cdot h \cdot g \cdot t \tag{3a}$$

For h, g, t, $D_m$, $k_1$ and $k_2$, see Equations (1) and (2);
$x_e$ = the depth of soil frost (cm) at the end of the period of t days,
$P_d$ = the absolute value of the sum of negative daily mean temperatures ($^oC$ d) during the period before the considered date, and
$0.5 \cdot h \cdot g \cdot t$ = the reduction of soil frost due to the heat flow upwards in the ground.

Considering further that $k_2$ decreases and $k_1/k_2$ increases with $P_d$ so that on the Arctic Circle the latter is greater by 50% than in south-western Finland, we note that in Equation (3a) the depth of soil frost increases with P at a lower rate than to the power of 0.5, (i.e. $\partial x_e/\partial P_d < h \cdot P_d^{-0.5}$); this holds especially for cases of thick snow because in this equation $D_m$ is multiplied by $k_1/k_2$. We also note that the depth of soil frost decreases with $D_m$ at a slightly decreasing rate. The last term can be approximated as a constant, because its decrease northwards with the decrease in the heat storage in the ground is mostly counteracted by the increase of the duration of soil frost, and also because the most deviating region in this respect, the northern boreal zone, is excluded from consideration.

Correspondingly, *Mustonen* (1966) gives for soil frost on March 31 the equation

$$x_e = 19.5 \cdot \ln P_d - 17.8 \cdot \ln D_m - 55 \tag{3b}$$

where $\partial x_e/\partial P_d$ is proportional to $P_d^{-1}$ and $\partial x_e/\partial D_m$ is proportional to $D_m^{-1}$.

In the cases of snow depths that are above average, we can approximate equations (3a) and (3b) by equation (4), behaving very similarly in respect of frost sum and snow depth:

$$x = b \cdot P^a / D + c \tag{4}$$

in which a, b, and c are constants, P = the sum of the absolute values of negative hourly mean temperatures ($^oC$ h) and D = snow depth in cm on March 15th. The value of a, less than 0.5, was obtained empirically (below).

When defining the frequency of years with unfrozen soil during the whole winter (F) as the frequency of winters with the maximum depth of soil frost below a certain limit, and denoting the reduced Gumbel variable, corresponding to F, by y, we have (*Helminen* 1997, *Reiss and Thomas* 1997)

$$y = -\ln(-\ln(1 - F)) \tag{5}$$

Considering that y is approximately linearly proportional to x, we obtain

$$-\ln(-\ln(1 - F) = d \cdot P^a / D + f \tag{6}$$

where D corresponds to a certain percentile in the distribution of snow depth on March 15th, and the values of d and f are constants, d being positive.

A regression analysis can be made, in which the values of the left-hand-side of Equation (6) are explained by the values of variable $P^a/D$. From the resulting regression equation, D can be solved for certain values of F. From charts showing D and $P^a$ with a high regional resolution, a chart analysis of the proportion of winters with unfrozen ground can be made by drawing isopleths for selected values of F.

The definition of variables F, P and D in the regression analysis is needed, as well the breath of the observational material. When defining F, the ground was regarded as unfrozen whenever the maximum depth of soil frost during the winter, as observed by readings of methyl blue tubes, was 8 cm or less. Considering P, differences between regions are rather similar in all winters; values increase smoothly from the south-west and the coasts to the north-east and inland. Consequently, a long period mean can be used. Because temporal variations in the variable $P^a$ are appreciably smaller than those in P, the differences of means between periods are insignificant. Therefore, means for the period 1955–1975 (*Soveri and Varjo* 1977) could be used.

The region where the relationship between soil frost, frost sum and snow depth can be given by one and the same equation, comprises the southern and middle boreal climatic zones (Chart 1). Around the boundary belt between the middle and northern boreal zones, unfrozen ground occurs slightly less frequently than in Southern Finland, and in the main parts of the northern boreal zone unfrozen ground hardly ever occurs; the heat storage in the ground in autumn is insufficient to prevent soil frost. The soil frost stations of Ylitornio, Kuusamo and Kemijärvi, located at or just north of the northern boundary of the middle boreal zone, were therefore neglected in the regression analyses.

Regression analyses according to Equation (6) were carried out separately for the following cases of snow depth values from:
1) the grid point chart for open fields,
2) the grid point chart for forests,
3) soil frost sites on open fields and
4) soil frost sites in forests.

In the regression analyses using grid point values of snow depths (1919–1962), observations at Ylistaro, and for the part of forests at Kiuruvesi, were rejected because the frequencies of unfrozen ground were obviously unrepresentative for their regions due to the unrepresentative snow depths observed at the sites of the soil frost observations. All in all, regression analyses of Equation (6) thus comprised 20 to 22 pairs of variables.

The appropriate percentile in the temporal distribution of snow depth, corresponding to the value of D in equation (6), should be of the same order of magnitude as the probability of unfrozen ground (F), being 3 to 25 per cent in the major part of Finland; in this way, the inaccuracy due to the possible differences between the temporal distributions of snow depth and the depth of soil frost is minimised. Therefore, for snow depths on March 15th in open places 1919–1962, the third highest of the 44 values were used in equation (6); these values are exceeded in 6% of winters and are denoted by $D_6$. In the Karelian areas, lost in 1944, the second highest values were used because the observation period was so short that these values better approximate $D_6$. Considering the snow depths observed at the soil frost sites on March 15th over the soil frost observation period of about 20 years, values of $D_6$ were approximated by the means of the first and second highest values.

The appropriate exponent for the frost sum P was chosen empirically, by solving equation (6) with various values of a. Values ranging from 0.20 to 0.33 gave the highest correlation coefficients. The value 0.33 was chosen, because for this value Equation (6) also gives satisfactory results when applied up to 100 km north of the northern boundary of the middle boreal zone (Chart 1). Consequently, $\partial x/\partial P$ is proportional to $P^{-0.67}$.


Chart 1. The southern (S), middle (M) and northern (N) boreal climatic zones of Finland with the boundary belt between zones S and M (hatched area, denoted by S/M), and the boundary line between the southern and middle boreal forest vegetational zones (*Kalela* 1960) (bold line).

## *4. Results*

The four solutions of equation (6) are as follows:

Fields, snow depths at grid points

$$y = -2.77 + 10.67 \cdot P^{033} / D_6 \tag{7a}$$

correlation coefficient = 0.68

Forests, snow depths at grid points

$$y = -3.63 + 14.84 \cdot P^{033} / D_6 \tag{7b}$$

correlation coefficient = 0.55

Fields, snow depths at soil frost observation sites

$$y = -0.52 + 7.12 \cdot P^{033} / D_6 \tag{7c}$$

correlation coefficient = 0.49

Forests, snow depths at soil frost observation sites

$$y = -0.41 + 4.04 \cdot P^{033} / D_6 \tag{7d}$$

correlation coefficient = 0.54

In order to develop solutions suitable for preparing charts, values of $D_6$ were found first from equation (7a) for fields and from equation (7b) for forests, corresponding to values of
$F_1$ = 6.5, 12.5 and 20.5%, and to values of
P = 10 000, 15 000, 20 000, 25 000, 30 000, 35 000 and 40 000 ($^oC$ h) (procedure 1).

The solutions were then substituted into equations (7c) and (7d) to obtain values of F, as follows
for fields (equation (7c)) $F_{2a}$ = 4.2, 6.8 and 9.3%, and
for forests (equation (7d)) $F_{2b}$ = 11.2, 13.3 and 15.0%, respectively (procedure 2).

In the final results, the values of $D_6$, obtained in procedure 1, were "labelled" with values of F as follows:

$F_{3a} = 0.5\ (F_1 + F_{2a})$ = 5, 10 and 15% (for fields)

$F_{3b} = 0.5\ (F_1 + F_{2b})$ = 8, 13 and 18% (for forests).

This method of calculating the final results was used to minimise maximum errors (Chapter 5). Two charts, one for fields, showing areas separated from each other by the isopleths $F_{3a}$ = 5, 10 and 15%, and another for forests, showing areas separated from each other by the isopleths $F_{3b}$ = 8, 13, and 18%, were prepared on the basis of the grid point charts of $D_6$ in fields and forests, and the chart of the frost sum (*Soveri and Varjo* 1977).

Results in the form of tables were prepared for frost sums P ($^oC$ h) corresponding to conditions in south-western Finland (P = 15 000), central inland Finland (P = 25 000) and the eastern and northern parts of the area south of the Polar circle (P = 35 000) (Tables 1 and 2).

In Tables 1 and 2 we see that the probabilities of 10 and 15% for unfrozen ground in forests correspond to slightly (4 to 8 cm) deeper snow cover than in open fields, or for the equal snow depths the probability of unfrozen ground in forests is 3 to 4 percentage units smaller than in open fields. However, comparing charts for both main land types (Charts 2 and 3), the frequency of unfrozen ground in forests is about 0 to 6 percentage units higher than in open fields because the average snow cover is greater in the forests, though regional differences do exist. In the middle and northern boreal zones (Chart 1) the branches of conifers intercept less snowfall than in the southern boreal zone; therefore, in the former zones the surplus of snow in forests over fields suffices to cause less soil frost in forests than in fields, whereas in the southern boreal zone soil frost conditions in both fields and forests are about equal.

Table 1. Snow depths on 15th March in open fields, exceeded in 6 per cent of winters ($D_6$), corresponding to 5, 10, and 15 per cent frequencies of unfrozen ground (F), at various frost sum (P) levels.

| P ($^{o}$C h) | $D_6$ (cm) for F = 5% | $D_6$ (cm) for F = 10% | $D_6$(cm) for F = 15% |
|---|---|---|---|
| 15 000 | 48.1 | 55.0 | 62.0 |
| 25 000 | 57.0 | 65.3 | 73.5 |
| 35 000 | 63.8 | 73.0 | 82.2 |

Table 2. Snow depths on 15th March in forests, exceeded in 6 per cent of winters ($D_6$), corresponding to 9, 13, and 18 per cent frequencies of unfrozen ground (F), at various frost sum (P) levels.

| P ($^{o}$C h) | $D_6$ (cm) for F = 8% | $D_6$ (cm) for F = 13% | $D_6$ (cm) for F = 18% |
|---|---|---|---|
| 15 000 | 57.9 | 64.9 | 71.7 |
| 25 000 | 68.6 | 76.9 | 85.1 |
| 35 000 | 76.7 | 86.0 | 95.2 |

The values of $D_6$ in the left-side columns of Tables 1 and 2, corresponding to about the same percentiles of F, are really about the same as expected on the basis of a consideration of equation (1) in Chapter 2, both in south-western Finland (the uppermost row) and on the Arctic Circle (the lowest row).

## *5. Discussion: The accuracy of the results*

A short discussion is required on the difference between the values of F obtained with values of $D_6$ from observations at frost sites (equations (7c) and (7d)) and those from values from grid point charts (equations (7a) and (7b)). At the soil frost observation sites, snow depths in the forests are mostly less than in the fields, whereas at the grid points, the relation is reversed. The snow depths at the soil frost sites are thus not fully representative in this respect; the fields at the sites are rather small and the forests rather tall and dense. However, these observations should not be ignored, because soil frost and snow depths are observed at the same sites. On the other hand, snow depths at a single place may vary during the winter due to drifting snow, so that a single observation on March 15th may be less representative for finding the soil frost conditions than a grid point value for that day based on tens of observations, a fact which is seen as higher correlation coefficients in the case of grid points depths in the regression equations. All in all, to minimise the maximal error, the averages of the frequencies of unfrozen ground, obtained by both methods, were used.

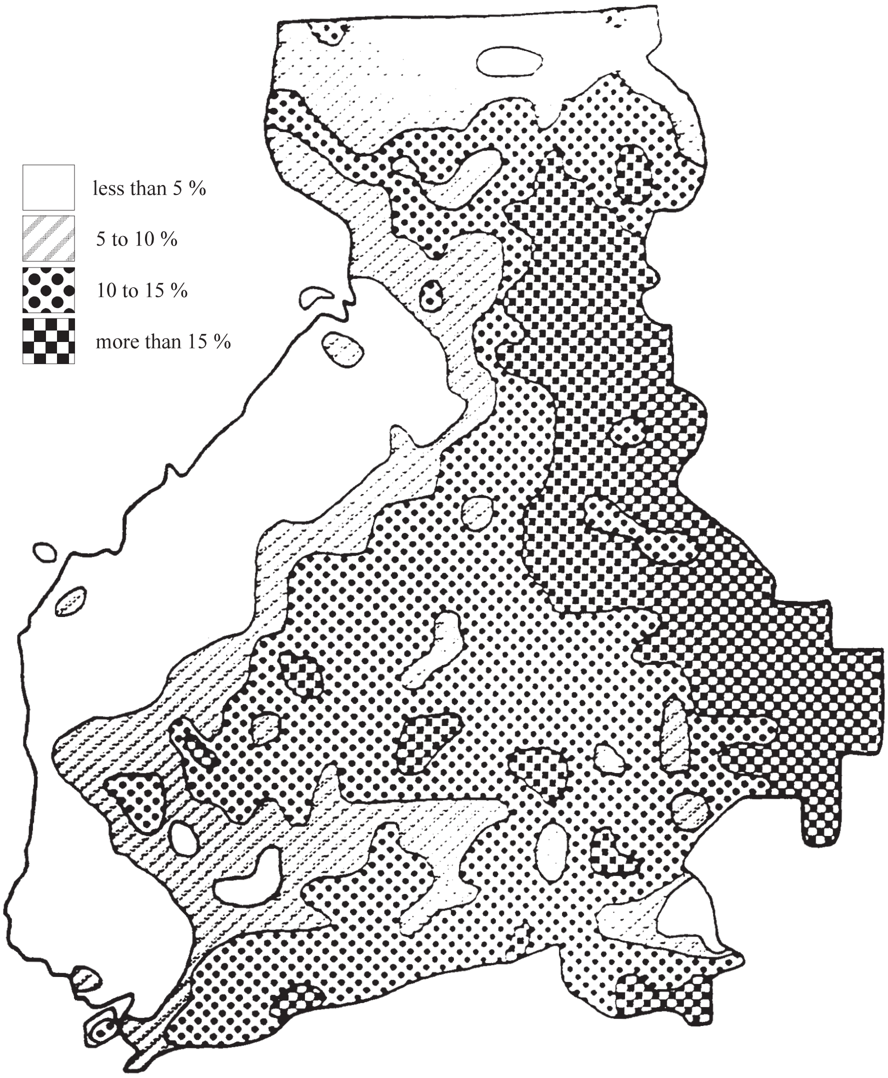


Chart 2. Regions with different probabilities of the occurrence of unfrozen soil throughout winter in open fields.

The observation periods for soil frost were not the same as those for the frost sum. The difference of the mean frost sums between the periods was studied for some places in various parts of Finland. In southern and western Finland frost sums for the observation period of soil frost were somewhat less than for the frost sum period 1955—1975, while in eastern and northern Finland they were about equal. Considering however, the parameter used, $P^{0.33}$, the influence of the differences between the periods in terms of the probability of unfrozen ground are only some tenths of one per cent and in terms of snow depths not more than 1 cm, i.e. they are insignificant.

Concerning forests, the probability of unfrozen ground is around 13%. Consequently, the best fit for the snow depth variable in regression equations (7b) and

(7d) would have been $D_{13}$ instead of $D_6$. Errors were examined by using temporal distributions of snow depth for forests in a sample of 18 regions. The mean error of the Gumbel variable y in these equations, caused by the use of $D_6$ instead of $D_{13}$ can be approximated as
$E_1$ = standard deviation of $(c \cdot (P^{033}/ D_{13} - P^{033}/ D_6)$
where c = 9.4 is the mean of coefficients in equations (7b) and (7d).

Correspondingly, the maximum error can be approximated as
$E_2 = 0.5 \cdot \max ((9.4 \cdot (P^{033}/ D_{13} - P^{033}/ D_6)) - 0.5 \cdot \min (9.4 \cdot (P^{033}/ D_{13} - P^{033}/ D_6))$.

Considering that F = 0.13 for y = 1.97 (equation (5)), we note that

the mean error of F = F (y = 1.97 + $E_1$) - 0.13, and
the maximum error of F = F (y = 1.97 + $E_2$) - 0.13.

As a result, the mean error of F is 0.010 and the maximum error 0.018; considering that within Finland south of the Arctic Circle F varies from 0.030 to 0.230, it is safe to conclude that no significant error was made by using values of $D_6$ instead of $D_{13}$ in forests.

In Charts (2) and (3), F was analysed similarly throughout the considered area. Thus, the values of F become slightly overestimated in the north-eastern corner of the area, i.e. within the northern boreal zone (Chart 1). The overestimation in F, according to soil frost observations at Kuusamo, Ylitornio and Kemijärvi, is less than 0.05. North of the Arctic Circle, the error is more serious, and the method presented in this study cannot be applied there.

In general, the differences in the occurrence of soil frost between forests and fields as obtained here seem to agree with common sense. According to Charts 2 and 3, winters with unfrozen soil occur slightly more frequently in forests than in open fields, especially in the middle boreal zone. This is caused by the fact that there is more snow in the forests, because for equal snow depths in forests and fields, the probability of unfrozen ground in forests is slightly lower (Tables 1 and 2). Such a difference is expected because in autumn the heat storage in the ground in forests is reduced by a reduced net radiation balance during the preceding summertime. The heat conductivity of the humus layer in forest ground increases linearly with water content while for cultivated soils it increases at a lower rate than to the power of 1 (*Jansson* 1991); thus, in summer when the water content of humus is low, the heat flux into the ground in forests is rather low, whereas in autumn, when the ground is wet, the heat loss from forest ground is rather large. On the other hand, any such difference between forests and open fields is small because some factors reduce the soil frost in forests more than in fields. The canopies of trees act as a greenhouse, which lessens the loss of heat in autumn and in winter in forests compared to fields. During situations of surface inversion, air is also stirred vertically under canopies. So, the frost sum in winter is slightly less in the shield of trees than in open places; further, the density and heat conductivity of the snow in forests are less.

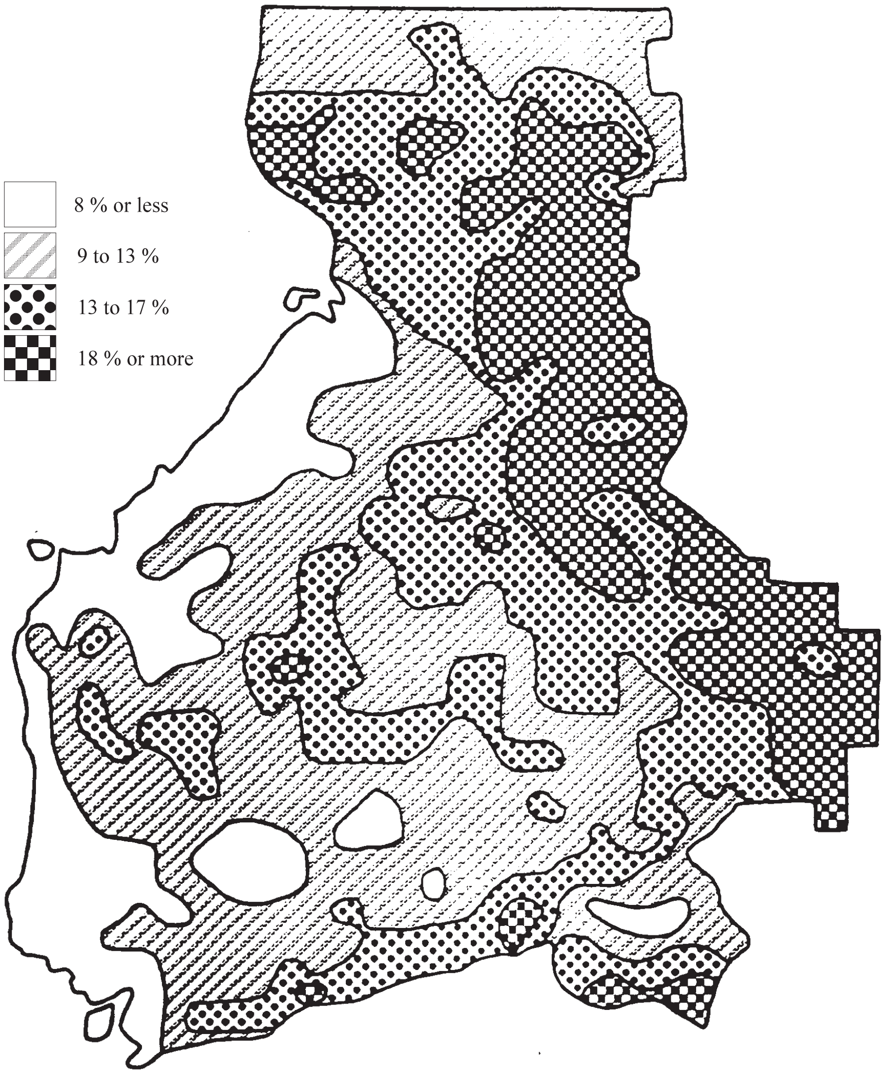


Chart 3. Regions with different probabilities of the occurrence of unfrozen soil throughout winter in forests.

Considering that the regional distribution of snow conditions in the Fennoscandian climate is very complicated, even regional features of the mean depth of soil frost, analysed on the basis of soil frost observations, e.g. the division of Finland into five areas (*Soveri and Varjo* 1977), are highly smoothed. Moreover, the regional distribution of the frequency of unfrozen ground is somewhat different from that of the mean depth of soil frost. Particularly in regions of low winter precipitation, as in westernmost Finland and in the southern Lake-Finland, the temporal variation of snow depth is small and the frequency of unfrozen ground smaller than expected on the basis of the mean depth of soil frost, while the opposite holds for regions where abundant precipitation is combined with rather mild winters, e.g. in the province of Uusimaa, north of the Gulf of Finland.

The main aim of this study, to display the spatial variation in the frequency of occurrence of unfrozen ground over winter with a high resolution both in forests and fields, has been achieved. On the other hand, the mean difference of the frequency between forests and fields, as well as the mean level for both main land types still remain somewhat inaccurate, demanding additional research.

## *6. Ecological, silvicultural and agricultural aspects*

The fact that the snow cover in forests, compared with open fields, in the middle and northern boreal zones (Chart 1) is deeper than in the southern boreal zone, implies an adaptation of vegetation to the particular climatic conditions in the two former zones. In the middle boreal zone, where the storage of heat is particularly significant due to its northern location, more shrubs and less growing stands are advantageous in this respect: Shrubs have a low albedo, not much higher than that of conifers (*Solantie* 1988), but allow more radiation to reach the ground, and transpire less than conifers. During winter, branches hold less snow than those in the southern boreal zone. This increases snow accumulation on the ground and reduces soil frost, which both favours the wintering of many perennials and accelerates the start of growth in the spring. Frozen soil is, however, more advantageous in many respects. A frozen soil, having a snow cover to protect against freezing kill, reduces attacks of snow mould fungi, respiration loss, and exhaustion of reserve carbohydrates. Consequently, unfrozen soil favours some species and penalizes others. Particularly, trees, perennials and biennials having large roots as a store for carbohydrates, may make use of unfrozen ground. The course of the line between the zones of the southern and middle boreal forest vegetation (*Kalela* 1961) within the boundary belt between the corresponding zones for the warm season climate (Chart 1), when considered together with the chart of soil frost conditions in forests (Chart 3), indicates the advantage of only shallow soil frost for forest vegetation as well for the timber-producing capacity of forests (falling below 4 $m^3$ per hectare northwards across the forest vegetational boundary (*Ilvessalo* 1960, Chart 30)).

In forests having large, dense stands, typical of the southern boreal zone, snow falling from the branches of trees, especially Norway spruce, is directed into the spaces between the trees, resulting in more snow and less soil frost than on average for forest ground. During a natural succession, sites of single trees and the spaces between them slowly migrate across the forest floor as a whole together with sites of unfrozen soil and micro-organisms intolerant of soil frost (*Solantie* 1993). Consequently, species intolerant to deep and long-lived soil frost may also succeed, and decomposition occurs well throughout the forest floor.

In Finland, the probability of unfrozen ground broadly increases towards the east-south-east, and the duration of frozen ground decreases in this direction. The regional occurrence of many perennials and some tree species (e.g. *Tilia cordata*) is dependent on this factor (*Solantie* 1993). The occurrence of unfrozen ground may also have affected Finnish history through agriculture. The occurrence of unfrozen ground varies somewhat with temporal changes in winter climate. However, the regional distribution of this risk is rather conservative with respect to climatic changes, because it is for the major part determined by topography and the location of large watersheds, significantly determining temperature distribution and orographic precipitation. Therefore, the application of recent conditions to earlier periods in time is justifiable. Wintering tillers of Scandinavian rye suffer from snow mould fungi under a thick snow pack on unfrozen ground. On the other hand, an eastern cultivar of rye, "juureinen" (= "root rye"), succeeding only in a slash-burn system, is more resistant to this pest. An advantage in this respect is its larger root system (*Valle* 1931, *Keskitalo* 1964), acting as a good store for carbohydrates; the seed is stored in the Nordic Gene Bank at Alnarp in Sweden, and new cultivation experiments are planned by Finnish researchers. Due to the abovementioned characteristics of this cultivar, the slash-burn culture spread westwards to the belt where the risk of unfrozen ground in open places is around 8 %, beginning in about the 12$^{th}$ century. In Chart 4, showing the relationship in the 1830:ies, the slash-burn method had already receded in some parts of the southern areas of the slash-burn culture. In Sweden, too, only new settlers from the Finnish slash-burn culture could establish agricultural settlements in those parts of Sweden (and eastern Norway) where the risk of unfrozen ground under snow in open fields exceeds 10% (*Solantie* 1990a).

The Karelian slash-burn culture started to spread westwards and north-westwards in the 11$^{th}$ and 12$^{th}$ centuries, and ended its spread in Norwegian Finnskogene five centuries later. But what is the origin of the "juureinen" in Finnish Karelia? Until the 11$^{th}$ century, the old agricultural settlement in East Finland, as well as in Karelia, was tightly restricted to small regional niches where the risk of unfrozen ground was less than 10% (Chart 2); this holds approximately also for northern Russia. In an area east-south-east of Karelia, there was, however, an agricultural settlement with an exceptional location. A Baltic-Finnish tribe, the Vepsians, lived in the Viking Age (and still lives to-day) on a highland east-south-east of Lake Ladoga situated more than 200 m above sea level around the main divide between the Baltic and Volga basins (e.g. *Pimenov and Strogalstsikova* 1994). This highland has a thick snow cover, frequently on unfrozen ground. In the 11$^{th}$ and 12$^{th}$ centuries, Vepsians had an economically significant culture, having lively trade intercourse with their neighbours, including the Karelians on the western side of lake Ladoga *(Pimenov and Strogalstsikova* 1994). It is therefore possible that the Vepsians cultivated "juureinen", and that the Karelian people adopted that cultivar at about the beginning of their large colonisation push into westerly regions.

In Karelian folk poetry, forming the basis for the Finnish national epic Kalevala, the mysterious Sampo plays a key role as a source of bread and welfare. Considering that Sampo was born and grown in the ash of burnt land and had its root in the ground, it is natural to assume that Sampo is simply a synonym for the word “juureinen” (*Solantie* 1990b) instead of the usual explanation “sky pole”. Both the hypothesis of the origin of “juureinen” and the meaning of Sampo agree well with the particularly frequent occurrence of the words ”Samb” and ”Sambas” in place names in the Vepsian highlands, particularly so in the names of lakes located in watershed regions between villages. Mullonen, a researcher of Vepsian culture, has also studied Vepsian placenames (*Mullonen* 1994). She recognises the connection between words such as ”samb”, ”sambas” and ”sampo” but cannot find the meaning ”sky pole” for ”sampo” as suitable for the word ”samb”. On the other hand, she mentions that many Vepsian placenames are derived from agriculture. Concerning plant names, the most significant cultivated species were favoured in place names. Considering this pragmatic name-giving practice, and the fact that small lakes were the most convenient and precise fixed points to describe the location of slash-burn fields in forests, the above explanation of ”sampo” seems natural. Generally, many concepts in the culture of our ancestors may have rather practical than mythical meanings, if understood in the light of the natural sciences.

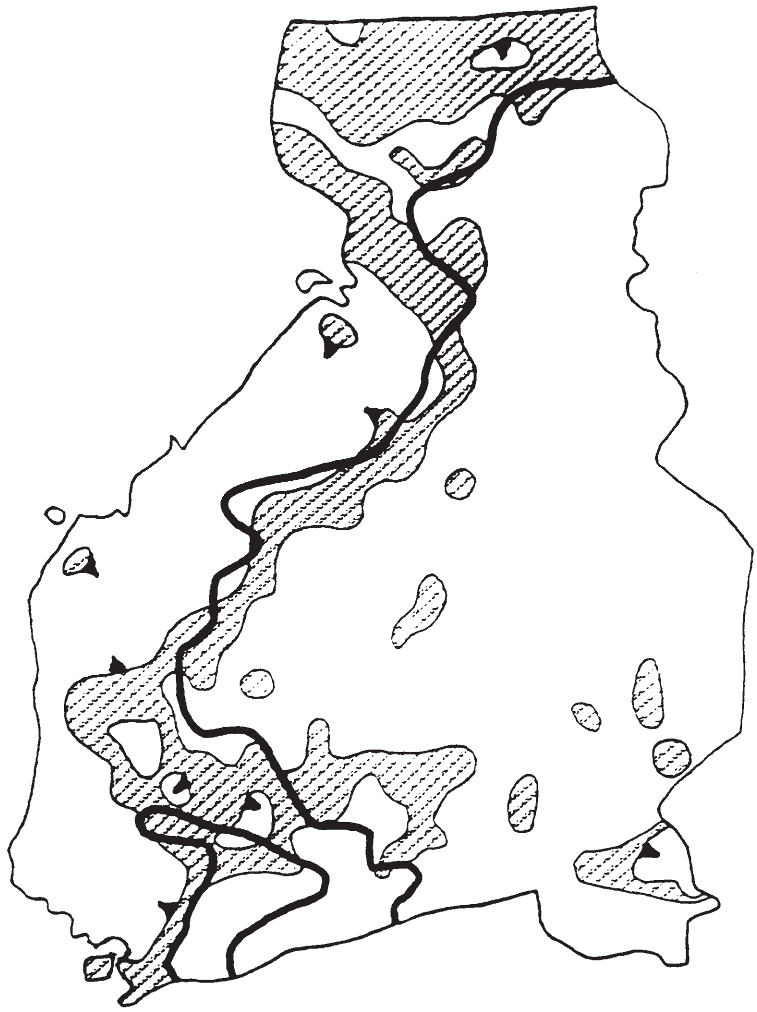

Chart 4. Region with a frequency of 5 to 10% of unfrozen soil in fields (hatched area), and the western boundary of the area of slash-burn culture in 1830:s (bold line), the area of this culture comprising also

an isle in the western part of province of Uusimaa (according to *Soininen* 1974). The teeth at the boundary of the hatched area show towards lower frequencies.

*References*


Andersson, S., 1964. Markfysikaliska undersökningar i odlad jord XV. Undersökningar av tjälbildning, tjäldjup och av tjälsmältning i olika åkermarker med och utan naturligt snötäcke. English Summary. *Grundförbättring 3. 1964, årgång 17*, p. 187–216.

Grandahl, R., 1957. Bestämning av tjälgräns i mark med enkel typ av tjälgränsmätare. *Grundförbätteing 1, årgång 10*.

Helminen, J., 1997. Lecture on extreme value distributions at the 8th Nordic Climate Workshop/3rd Reward Meeting, Helsinki 25.-27.2.1997. Mimeograph.

Huttunen, L. and J. Soveri, 1993. Luonnontilaisen roudan alueellinen ja ajallinen vaihtelu Suomessa. *Vesi- ja ympäristöhallinnon julkaisuja* 139 - *sarja A*. Publ. by Vesi- ja ympäristöhallitus. Helsinki.

Ilvessalo, Y., 1960. Suomen metsät kartakkeiden valossa. Summary in English: The forests in Finland in the light of maps. *Comm. Inst. For. Fenn. 52.2.*, 70 p.

Jansson, P.-E., 1991. Simulation model for Soil Water and Heat conditions. *Report 165. Swedish University of Agricultural sciences*. Uppsala 1991, 73 p.

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

Keskitalo, O., 1964. Hausjärven historia, 880 p. Hämeenlinna.

Mukula, J., O. Rantanen, U. Lallukka and V. Pohjonen, 1976. Rukiin viljelyvarmuus Suomessa 1950–1975. *Kasvinviljelylaitoksen tiedote N:o 5*, 77 p. Maatalouden tutkimuskeskus, Jokioinen.

Mullonen, I. 1994. Paikannimistö vepsäläisen henkisen perinteen valottajana. In: Vepsäläiset tutuiksi. Kirjoituksia vepsäläisten kulttuurista. Ed. by Heikkinen, K.& Mullonen, I. 1994. *University of Joensuu. Publications of Karelian institute No. 108*, p. 41–50.

Mustonen, S. 1996. Ilmasto- ja maastotekijöiden vaikutuksesta lumen vesiarvoon ja roudan syvyyteeen. *Acta Forestalia Fennica 79*.

National Board of Waters, Finland 1975, 1976, 1977, 1980, 1981, 1983, 1987. *Hydrological yearbooks 1971–1983.*

National Board of Waters and the Environment 1990, 1991, 1992, 1993. *Hydrological yearbooks 1984–1990.*

Pimenov, V. and Z. Strogalstsikova, 1994. Vepsäläisten etnisen kehityksen ongelmista. In: Vepsäläiset tutuiksi. Kirjoituksia vepsäläisten kulttuurista. Ed. by Heikkinen, K.& Mullonen, I. 1994. *University of Joensuu. Publications of Karelian institute No. 108*, p. 19–40.

Reiss, R.-D. and M. Thomas, 1997. Statistical Analysis of Extreme Values. Birkenhäuser Verlag, Basel, 336 p.

Reuna, M., J. Perälä and S. Aitamurto, 1993. Lumen aluevesiarvoja Suomessa vuosina 1946–1993. English Abstract: Areal snow water equivalent values in Finland in the years 1946–1993. *Vesi- ja ympäristöhallinnon julkaisuja - sarja A 165*, 287 p. National Board of Waters and Environment.

Samnordisk planteforedling, 1988. Vinterherdighet 1. *SNP-Publikation Nr. 19, October 1988*. Nordiska Ministerrådet, Copenhagen.

Soininen, A. 1974. Vanha maataloutemme. Maatalous ja maatalousväestö Suomessa perinnäisen maatalouden loppukaudella 1720-luvulta 1870-luvulle. Abstract: Old traditional agriculture in Finland in the 18th and 19th centuries. *Journal of the scientific agricultural society of Finland, Vol.* 46. *Supplement*. Helsinki.

Solantie, R. 1988. Albedo in Finland on the basis of observations on aircraft. *Meteorological publications 12*. Publ. by the Finnish Meteorological Institute, 106 p. Helsinki.

Solantie, R. 1990a. De klimatologiska förutsättningarna för rågodling som förklaring till bosättningens utbredning i Mellansverige med särskilt hänsyn till migrationen mellan Finland och Sverige. *Historisk Tidskrift för Finland I 1990 årg. 75p. 43—68* (in Swedish).

Solantie, R. 1990b. The climate of Finland in relation to its hydrology, ecology and culture. *Finnish meteorological institute contributions No. 2*, p.130 p. Finnish Meteorological Institute.

Solantie, R. 1993. Snow and soil frost in Finnish forests: Ecological interdependencies between climate, fauna and early culture in the province of Uusimaa. *Silva Fennica 1993, Vol. 27, N:o 3*, p. 295–301.

Soveri, J. and M. Varjo, 1977. Roudan muodostumisesta ja esiintymisestä Suomessa vuosina 1955—1975. *Vesientutkimuslaitoksen julkaisuja* 20. English summary: On the Formation and Occurrence of Soil Frost in Finland 1955 to 1975. *Publications of the Water Research Institute* 20. Publ. by Vesihallitus – National Board of Waters, Finland. Helsinki.

Valle, O., 1931. Erään suomalaisen kaskiruiskannan historiaa. *Pellervo* No 6/1931, p. 118–121.