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Model Computations on the Climate Change Effects on Snow Cover, Soil Moisture and Soil Frost in the Boreal Conditions over Finland

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This study considered how climate change affects the accumulation of snow, the soil moisture and soil frost at sites without tree cover in boreal conditions in Finland (60°–70°N). An increase of 4.5 °C in annual mean temperature and 20 % in annual precipitation were assumed for Finland by the year 2100 according to A2 emission scenario. Along with climate, the soil type of the permanent inventory plots of the Finnish National Forest Inventory was used. Soil and climate data were combined by using a process-based ecosystem model. Calculations were done for four periods: current climate (1971–2000), near future (2001–2020), mid-term future (2021–2050) and long-term future (2071–2100). According to our simulations, the average monthly duration and depth of snow decreased over the simulation period. However, the increasing precipitation may locally increase the snow depths in the mid-term calculations. In the autumn and winter, the average volumetric soil moisture content slightly increased in southern Finland during the near future, but decreased towards the end of the century, but still remained on a higher level than presently. In northern Finland, the soil moisture in the autumn and winter increased by the end of this century. In the summertime soil moisture decreased slightly regardless of the region. Throughout Finland, the length and the depth of soil frost decreased by the end of the century. In the south, the reduction in the depth was largest in the autumn and spring, while in the mid-winter it remained relatively deep in the middle of the century. In the north, the depth tended to increase during the first two calculation periods, in some areas, even during the third calculation period (2071–2100) due to reduced insulation effects of snow during cold spells. The wintertime increase in soil moisture and reduced soil frost may be reflected to reduced carrying capacity of soil for timber harvesting.

Keywords A2 climate scenario, climate change, precipitation, snow accumulation, soil carrying capacity, soil frost, soil moisture, temperature
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1 Introduction

In northern Europe, including Finland, climatic change is expected to raise the mean annual temperature by 2–5°C during the next 100 years (IPCC 2001). Together with this development, the mean annual precipitation could increase by about 10–15% from its present level of 400–600 mm (Ruosteenoja et al. 2005). The increase is expected to be most in northern Finland; up to 40% in some areas (Ruosteenoja et al. 2005). However, the increased precipitation would probably not compensate for the increased evapotranspiration, excluding northern Finland, as demonstrated by Kellomäki et al. (2005, 2007). Shortage of soil water may limit the productivity of the forest ecosystem only in some areas as demonstrated by several model-based scenarios for northern Europe (e.g. Kellomäki et al. 2007). This is because low summer temperatures and the poor supply of nitrogen are currently the main factors limiting the forest growth in the boreal conditions, and the temperature elevation may reduce these limitations. However, in the continental parts of Scandinavia, the supply of water could become more limiting, because the temperature elevation may reduce the accumulation of snow and the duration of snow cover, these two phenomena being of prime importance in replenishing the reservoir of water in the soil and thereby the level of the ground water (Kellomäki and Väisänen 1996).

The effects of the climate change on soil frost are related both to the temperature conditions and the accumulation of snow (or depth of snow cover), both of which are likely to change under the climate change. According to earlier studies, the decrease in soil frost and snow cover in Finland is probably the largest in the early winter, but also in springtime (March–April) (Peltola et al. 1999, Venäläinen et al. 2001a, b). Snow cover slows the freezing of the soil due to the insulation, but on the other hand climate warming has also been stated to increase soil freezing because the climate may become drier and the amount of snow on the ground would be smaller (e.g. Isard and Schaetzl 1998). On the other hand, the increase in winter precipitation may result in the increased intensity of snowfall and the accumulation of snow (Jylhä et al. 2004, Carter et al. 2005, Ruosteenoja et al. 2005). In addition, soil temperature acting through frozen or unfrozen water has a substantial impact on water in the soil; i.e. how the soil water resources are controlled by climatic and edaphic factors.

In Scandinavia, timber is harvested all year-round, though mainly it is concentrated in the early autumn through to late winter or early spring. This implies that the soil moisture, the accumulation and depth of snow and the occurrence and depth of soil frost are of primary importance in affecting the trafficability of soil and thus the profitability of timber harvest operations. Wet soils are especially prone to damage in the soil profile caused by harvesting machines. On the other hand, snow cover and deep soil frost reduce damage to the profile, furthermore mechanized timber harvesting on peaty soils is successful only when the soil is frozen to a sufficient depth. The timing of thinning operations for the periods of frozen soil with adequate snow cover is especially important in order to avoid any excess damage to the roots of the remaining trees and thus avoid root rot and reduction of quantity and quality of timber being extracted later during the rotation.

This study considers how climate change (changes in temperature and precipitation) affects snow accumulation, soil moisture content and freezing of forest soil in boreal conditions in Finland (60°–70°N). The model computations cover a period of 100 years using sites without forest cover throughout the territory of Finland. The forest cover is excluded in order to avoid the variability in soil temperature and moisture, which is related to variability of thermal and moisture conditions on soil surface due to the influence of tree canopies to the incoming radiation and throughfall of water on the soil surface.

2 Computations

2.1 Model Outlines

Model Structure

The calculations utilised the ecosystem model developed by Kellomäki and Väisänen (1997)

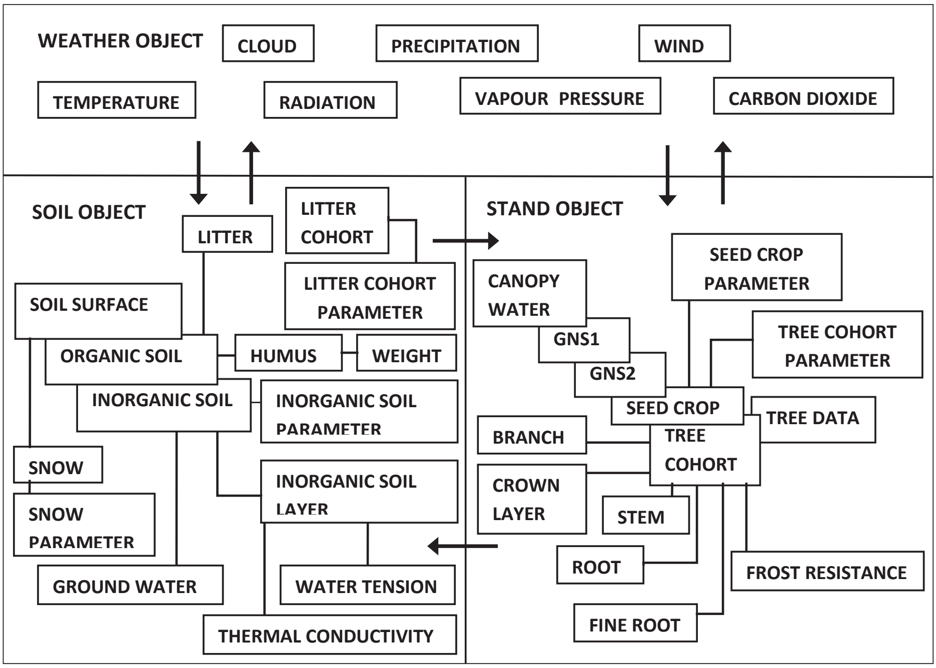

Fig. 1. Basic structure of the forest ecosystem model used in the calculations as a system of WEATHER, SOIL and STAND objects (Kellomäki and Väisänen 1996, 1997). In calculations, only WEATHER and SOIL objects were used.

in which the weather and soil factors control the growth and dynamics of forest. The model employs a time constant with a length that varies from an hour to decades, the basic time constant of the computations was an hour. The model is based on an object-oriented design implemented in C++. Only calculations important with regard to soil water and temperature are discussed here. For other details of the model, see Strandman et al. (1993), Kellomäki and Väisänen (1996, 1997) and Matala et al. (2003, 2005).

In the model's architecture, the SOIL object models the behaviour of humus and soil in terms of 1) heat and water transfer on the soil surface (SOIL SURFACE object), 2) organic soil (ORGANIC SOIL object) and 3) inorganic soil (INORGANIC SOIL object) in such a way that soil temperature determines whether the soil is frozen or not, with the consequent effect on water conditions in the soil (Fig. 1). The INORGANIC SOIL object models the heat and water conditions in the inorganic soil. Inorganic soil is divided into 12 horizontally homogeneous layers and no change in soil properties with time is assumed. Heat and water conditions are modelled with partial differential equations solved by Euler integration (Jansson 1991, Kellomäki and Väisänen 1997) (Eq. 1):

$$\frac{\partial W}{\partial t}=\frac{\partial}{\partial z}\left[k_W\left(\frac{\partial p}{\partial z}+1\right)\right] \tag{1}$$

Water and temperature conditions in the soil layer are calculated assuming a steady-state heat flow between the soil and the snow pack (Kellomäki and Väisänen 1997):

$$\frac{\partial CT}{\partial t}-L_f r_i\frac{\partial W_i}{\partial z}=\frac{\partial}{\partial z}\left(k_h\frac{\partial T}{\partial t}\right)-C_W\frac{\partial (Tq)}{\partial t} \tag{2}$$

In Eqs. 1 and 2, t is the time, W is the volumetric water content ($m^3\ m^{-3}$), W_i is the ice content ($m^3\ m^{-3}$), T is the temperature (°C) of the inorganic soil layer, and z is the thickness (m) of the inorganic soil layer. C is the heat capacity ($J\ m^{-3}$ $°C^{-1}$) of the inorganic layer of the soil, C_W is the

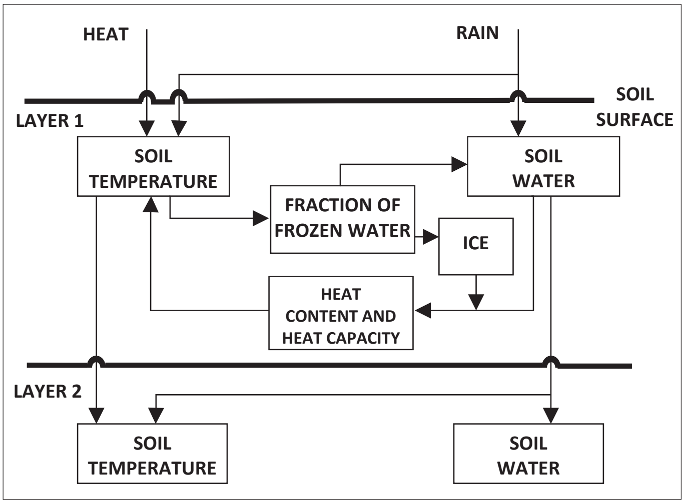

Fig. 2. Outlines of the interlinks between the processes related to the temperature and water in soil when the heat and moisture conditions in the soil layers were calculated (Kellomäki and Väisänen 1996, 1997).

heat capacity of water (J m^{-3} °C^{-1}), p is the water tension (mm water), k_h is the thermal conductivity (W m^{-1} °C^{-1}), k_w is the hydraulic conductivity (m s^{-1}), L_f is the latent heat of freezing (J kg^{-1}), q is the water flow (m s^{-1}) and r_i is the density of ice (kg m^{-3}).

The INORGANIC SOIL LAYER object, along with the THERMAL CONDUCTIVITY object and the WATER TENSION object, simulates the temperature and water conditions in the soil layers. For example, the availability of water for plants and the current temperature of the soil are updated. In these calculations, the processes related to the temperature and water in the soil are interlinked in such a way that the volumetric water content is dependent on the temperature of the soil through fraction of frozen water and evaporation of water from the soil (Fig. 2). Similarly, the water in the soil affects the soil temperature through heat content and heat capacity of the soil as related to its physical properties.

The lower boundary conditions for soil temperature, i.e. the heat flow from the lowest layer and percolation from the lowest layer, are calculated from an analytical solution of the heat flow equation, based on the sine variation of the annual mean air temperature (Kellomäki and Väisänen 1997). The unsaturated hydraulic conductivity is obtained from the empirical equation of Mualem (1976) and the thermal conductivity is calculated from an equation presented by Kersten (1949) and de Vries (1975). The behaviour of the snow layer is modelled in terms of the hydrological and thermal processes modifying the snow cover, assuming that the snow layer is homogeneous. The total water content of the snow layer is divided into liquid and frozen water. The melting and freezing of the water in the snow is determined by air temperature, solar radiation, precipitation and surface-soil heat flow as determined by Jansson (1991).

The total heat content of the frozen soil is partitioned into latent and sensible heat portions according to an empirical freezing-point depression function for soil (r) (Jansson 1991) (Eq. 3):

$$r = \left(\frac{E}{E_f} \right)^{b\lambda} \tag{3}$$

where r is expressed in terms of the ratio of the actual latent heat content to the latent heat content at –5°C, defining the minimum unfrozen soil water content in the model; b is an empirical constant that depends on the soil type; λ is the pore size distribution index; E_f is the total heat content at –5°C; and E is the actual total heat content given by the heat flow equation.

Correspondingly, according to Eq. 4. the sensible heat content (H) is (Jansson 1991):

$$H = E(1 - f_{lat})(1 - r) \tag{4}$$

where f_{lat} is the latent heat of ice as a fraction of the total heat content of the soil at –5°C.

The soil water flow under frozen conditions is based on an analogy between freezing/thawing and drying/ wetting. Water potential and hydraulic conductivity are calculated from the unfrozen water content, which in turn is obtained from the freezing-point depression function r (Jansson 1991).

Performance of Model

Previously, Peltola et al. (1999) found that the simulated soil frost results for the current climate conditions were generally in quite good agreement with the regular measurements of soil freezing, thawing and maximum depth of soil frost made by the Finnish Hydrological Office (Huttunen and Soveri 1993). In addition, the length of the period with frozen soil under natural conditions was simulated realistically with the model utilized in this study. Similarly, Venäläinen et al. (2001a) demonstrated a close correlation between the measured and simulated values of snow accumulation and soil frost in selected sites in Finland. Nevertheless, the model was further validated by comparing the simulated values of depth of soil frost with the measured values representing several soil frost measuring sites across the south–north gradient throughout Finland. Fig. 3 shows a close correlation between the measured and modelled timing of the freezing, but there is wide variability in the absolute depth of soil frost due to soil type, accumulation of snow and specific local conditions. In these calculations, the soil profile down to 140 cm was divided into 10 cm thick and homogenous layers. In addition, hydrological and nitrogen cycles included in the model have been separately validated by Laurén et al. (2005) against the long-term monitoring data representing these processes on the scale of a small watershed. A close correlation between the simulated and measured outflow of water and nitrogen from the watershed was found.

2.2 Input to Model Runs

Grid of Inventory Plots

The study covers 26 million hectares of forest land represented by the permanent sample plots of the Finnish National Forest Inventory. The sample plots were established by the Finnish Forest Research Institute in 1985. The plots are located in blocks of four plots in the south and three in the north. The blocks form a 16 km × 16 km grid in southern and a 32 km × 32 km grid in northern Finland. Only plots on upland mineral soils were used. The total number of plots was 1368. Most of them are located on sites of medium fertility or close to it, i.e., *Oxalis-Myrtillus* type (OMT, 256 sites), *Myrtillus* type (MT, 630 sites), *Vaccinium* type (VT, 361 sites) and *Calluna* type (CT, 121 sites). The simulations in this study were performed for the soils of all these plots and spatial interpolation was utilized in the generation of the soil frost maps over the whole Finland, for example.

The site type of the plots was used to define the soil type (Urvas and Erviö 1974), applying the classification of soils into rough till, fine till, gravel, sand, fine sand, silt, and clay (Talkkari and Hypén 1996). Most of the plots were located on unsorted coarse and fine till soils. The most common soil textures among the sorted soils were sand and fine sand. Regarding the soil type, the values of field capacity (the maximum water holding capacity) and wilting points (the lower limit at which water is available to plants) shown in Table 1 were used in calculating the water holding capacity of the soil in the plots down to 30 cm.

To initialize the simulations for a specific plot with the SOIL object models, the amount of litter and humus (soil organic matter, SOM) on the plots was defined on the basis of the thickness of the organic soil layer measured in the inventory. The thickness was converted into the mass of SOM using the bulk density of SOM considering the site type (Tamminen 1991, Talkkari and Hypén 1996). Thereafter, the mass of SOM was regressed against the prevailing temperature sum of the plot by the site types (Kellomäki et al. 2007). During the simulations, the amount of organic matter on and in the soil was constant.

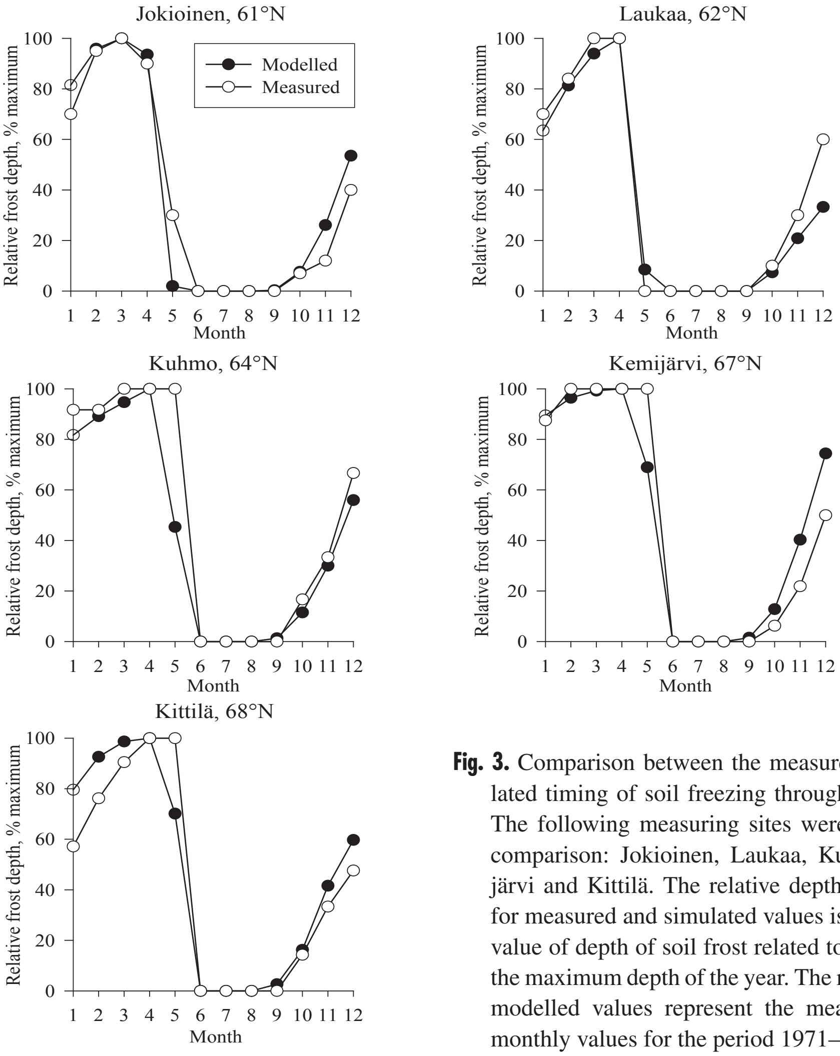

Fig. 3. Comparison between the measured and simulated timing of soil freezing throughout Finland. The following measuring sites were used in the comparison: Jokioinen, Laukaa, Kuhmo, Kemijärvi and Kittilä. The relative depth of soil frost for measured and simulated values is the monthly value of depth of soil frost related to the depth of the maximum depth of the year. The measured and modelled values represent the mean maximum monthly values for the period 1971–2000.

Climate Scenarios

The spatial resolution of the grid for the current climate (1971–2000) and for the climate change scenarios was 49 km × 49 km (Ruosteenoja et al. 2005) as provided by the Finnish Meteorological Institute. In both cases, the climate data represented the daily values for each season introducing the inter-annual variability around the trend-like changes in the climate. In the simulations for a given sample plot the calculation algorithm utilizes the values for the climate variables from the closest grid point of the climate data. The simulation results are shown over the whole

Table 1. Values of field capacity and wilting point used to describe the water holding capacity of soil in the top 30 cm soil layer.

Soil type	Field capacity (mm)	Wilting point (mm)
Rough moraine	60	9
Fine moraine	105	45
Gravel	12	0
Sand	15	3
Fine sand	75	6
Silt	120	30
Clay	126	75

Table 2. Mean duration of snow cover (days when snow cover >1cm) under the current climate and under the changing climate in three time slices in the period 2001–2100. In parenthesis, mean deviation.

Centre	Current	2001–2020	2021–2050	2071–2100
Rannikko	159.9 (14.2)	148.8 (17.1)	138.0 (19.5)	97.1 (24.4)
Varsinais-Suomi	165.5 (7.5)	155.3 (8.7)	146.5 (10.4)	108.7 (14.8)
Häme-Uusimaa	174.2 (4.6)	165.3 (5.2)	153.5 (4.4)	120.0 (4.9)
Kaakkois-Suomi	175.0 (4.8)	167.6 (6.1)	156.9 (6.2)	124.5 (11.2)
Pirkanmaa	177.5 (5.0)	168.7 (5.5)	160.3 (5.1)	126.6 (5.8)
Etelä-Savo	182.0 (4.1)	174.5 (4.6)	164.0 (5.5)	132.9 (6.3)
Etelä-Pohjanmaa	178.6 (4.2)	169.5 (6.9)	161.8 (9.5)	126.6 (14.7)
Keski-Suomi	183.1 (2.7)	175.3 (3.4)	167.5 (4.1)	136.2 (5.0)
Pohjois-Savo	188.7 (5.4)	181.1 (5.9)	174.1 (5.4)	144.6(6.7)
Pohjois-Karjala	192.5 (5.1)	185.7 (5.3)	176.3 (6.5)	148.0 (7.3)
Kainuu	201.4 (4.0)	194.8 (3.6)	188.7 (4.9)	164.6 (7.8)
Pohjois-Pohjanmaa	195.7 (12.0)	189.1 (12.3)	181.7 (13.4)	156.4 (19.0)
Lappi	216.3 (12.6)	209.4 (12.1)	202.2 (11.2)	184.8 (11.9)
Whole country	183.9 (15.1)	175.8 (16.4)	167.1 (17.5)	136.2 (23.6)

of Finland and separately for thirteen regional Forest Centres in Finland.

The climate change scenarios were given in three periods: i.e. 2001–2020, 2021–2050 and 2070–2099 based on the IPCC SRES A2 emission scenario (Ruosteenoja et al. 2005). In each period, the mean temperature and precipitation increase is representing the predicted mean increase according to climate scenario, which is supposed to occur at the mid-point of each period. The values between the mid-points are based on a linear interpolation between the values at two consecutive mid-points. By 2070–2099, the mean temperatures are projected to increase almost 4°C in the summer and more than 6°C in the winter. Wintertime precipitation is estimated to increase by more than 20% by then end of the century. In summer, precipitation is estimated to remain nearly unchanged.

In the analysis of the simulation outputs the duration of the snow cover represents the sum of the days over the year when the snow cover is thicker than 1 cm. Snow depth was calculated as an average over each month and further as an average over each period. Similarly, the duration of soil frost is the sum of days with the soil temperature in the uppermost soil layer smaller than 0°C.

3 Results

3.1 Snow Cover

Duration

Fig. 4 shows how the average duration of snow cover varies throughout Finland, if the current climate and the changing climate are assumed. In the coastal, and most of the southern parts of Finland, the duration of snow cover is from 160 to 180 days under the current climate (1971–2000). In these areas, the snow duration reduces slightly in the first calculation period (2001–2020), but substantially in the third calculation period (2071–2100). In the coastal, and most of the southern parts of Finland, the duration of snow cover may be 30% smaller than under the current climate by the end of this century. The duration of snow cover is also less in the more northern sites, however to a lesser extent. By the end of this century, the duration of snow cover in the most northern parts of the country may be up to 180 days per year implying a 15–20% reduction. There is a slight tendency that the variability in the snow duration increases towards the end of this century along with the elevated temperature and wintertime precipitation (Table 2).

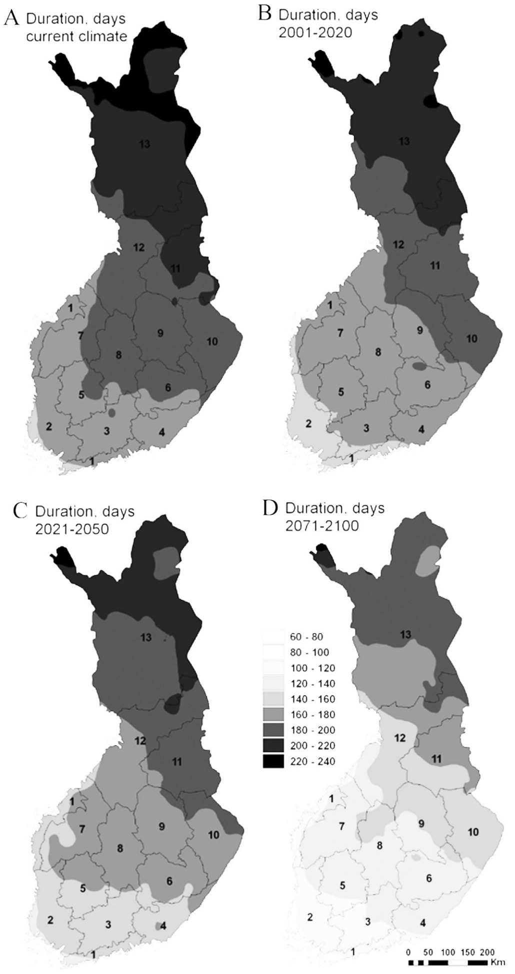

Fig. 4. Mean duration of snow cover (days when snow cover >1cm) under the current climate (A) and under the changing climate in three time slices in the period 2001–2100 (B–D). The numbers in the maps refer to the Forest Centres representing the forest administrative regions for forests in Finland: 1 Rannikko, 2 Varsinais-Suomi, 3 Häme-Uusimaa, 4 Kaakkois-Suomi, 5 Pirkanmaa, 6 Etelä-Savo, 7 Etelä-Pohjanmaa, 8 Keski-Suomi, 9 Pohjois-Karjala, 10 Pohjois- Karjala, 11 Kainuu, 12 Pohjois-Pohjanmaa and 13 Lappi).

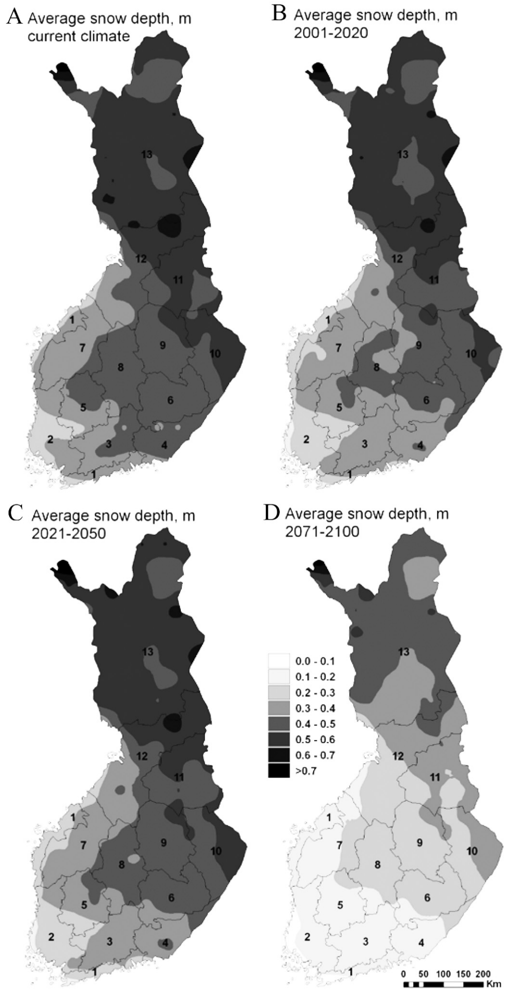

Fig. 5. Mean depth of snow cover (m) in January under the current climate (A) and under the changing climate in three time slices in the period 2001–2100 (B–D). See Fig. 4. for the numbers in the maps.

Depth

Fig. 5A shows how the average depth of snow cover varies throughout Finland, if the current climate (1971–2000) is assumed. Following the general temperature pattern, the average depth of snow cover in January exceeds 60 cm in the northern and north-eastern parts of the country. On the other hand, in the northernmost parts of northern Finland the mean depth remains below the average depth due to reduced precipitation compared

Table 3. Mean depth of snow cover (cm) in each Forest Centre in selected months representing the main period of snow cover when the climate in the current climate (1971–2000) is assumed. In parenthesis, mean deviation.

Centre	December	January	February	March
Rannikko	15.8 (6.9)	27.0 (8.7)	39.0 (10.2)	30.6 (8.5)
Varsinais-Suomi	17.8 (6.0)	30.3 (7.5)	43.1 (8.1)	32.6 (8.0)
Häme-Uusimaa	23.4 (3.6)	38.7 (4.9)	51.7 (5.8)	41.5 (5.5)
Kaakkois-Suomi	26.7 (5.4)	41.7 (5.9)	54.7 (5.7)	45.2 (4.6)
Pirkanmaa	25.2 (5.3)	39.2 (7.2)	52.1 (7.8)	43.0 (7.1)
Etelä-Savo	29.4 (3.4)	44.0 (3.4)	57.0 (3.8)	46.7 (4.5)
Etelä-Pohjanmaa	22.8 (5.7)	33.5 (7.6)	45.1 (8.5)	35.8 (6.0)
Keski-Suomi	29.7 (2.1)	43.8 (3.1)	56.9 (3.7)	47.1 (3.7)
Pohjois-Savo	33.4 (4.0)	47.1 (5.2)	60.3 (5.6)	51.3 (6.3)
Pohjois-Karjala	35.5 (3.0)	51.0 (3.5)	63.9 (3.4)	55.3 (3.6)
Kainuu	38.3 (3.7)	51.7 (4.1)	64.5 (4.4)	56.7 (5.2)
Pohjois-Pohjanmaa	34.7 (8.8)	47.9 (10.1)	61.1 (10.7)	54.1 (12.7)
Lappi	42.2 (8.2)	53.5 (8.3)	64.0 (8.5)	60.0 (8.4)
Whole country	28.9 (5.1)	42.3 (6.1)	54.9 (6.6)	46.1 (6.5)

to further south. In the central part of the country, the mean depth of snow cover is 40–50 cm, while it is 20–30 cm in the southern part, the smallest values representing coastal areas.

Regardless of the Forest Centre, the mean thickness of the snow cover peaks in February, varying from 40 cm in the south up to 60 cm in the north (Table 3). The variability in the depth of the snow cover is smaller in the Forest Centres situated in the east or north (inland) than in those representing the southern and coastal areas of the country. These differences indicate the variability in the general weather pattern, which is more continental in the eastern and northern parts of the country compared to the western and coastal areas, where the climate is more maritime.

Figs. 5B–5D show that in the first calculation period (2001–2020), if changing climate is assumed, the mean depth of snow cover is less mainly in southern and central parts of country. This holds also for the second calculation period (2021–2050), however in the third calculation period (2071–2100) the depth of snow cover reduces substantially even in northern Finland. On the other hand, in the northernmost part of the country, the depth of snow cover may locally even increase because the increasing precipitation enhances the snow accumulation more than the snow melting is increased due to the higher temperatures.

Appendix 1 (Table A1) shows how the climate change may affect the snow accumulation throughout Finland in the different Forest Centres. Over the whole country, the mean depth of snow cover in December is about 14% smaller in the first calculation period (2001–2020) under the climate change than under the current climate. The depth reduction is less in January (9%), February (5%) and March (8%). The reduction is fairly similar throughout the country except in the northernmost Centre (Lappi), where the snow cover is slightly deeper (1%) under the climate change than under the current climate. In the second calculation period (2021–2050), the depth of snow cover is reduced further; i.e. the depth is 24% in December, 8% in February and 15% less in March than under the current climate. Again, the area of the Lappi Forest Centre is an exception, where the depth of snow cover increases by 2–5% under the climate change through December to March compared to that under the current climate. In the third calculation period (2071–2100), the depth of snow cover reduces substantially throughout the country including the area of the Lappi Forest Centre. The reduction is 59% for December, 49% for January, 47% for February and 61% for March.

In general, the decreasing mean depth of the snow cover towards the end of this century is mostly related to the higher temperatures in early

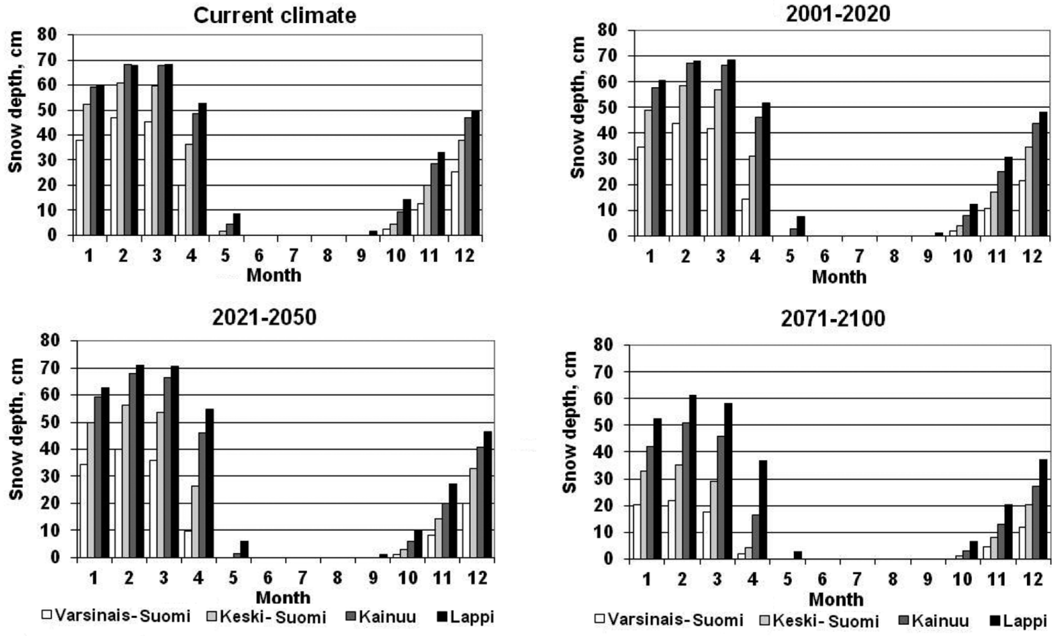

Fig. 6. Mean maximum values of snow depth (cm) in the selected Forest Centres representing the south–north gradient across Finland in different calculation periods.

and late winter with the reduction in the duration of snow cover. This holds also for the maximum snow depth for the Forest Centres shown in Fig. 6 on the monthly basis. In the first (2001–2020) and second (2021–2050) calculation periods, the maximum values reduce only slightly, mainly in early and late winter. In the third period (2071–2100), the maximum values fall substantially throughout the country along with the reduction of the duration of snow cover.

3.2 Soil Moisture

Fig. 7A shows how the soil moisture varies throughout Finland, if the current climate is assumed. Following the general patterns in temperature and precipitation, the values of soil moisture are larger in the southern and central parts of the country (>40%) than in the northern part (<40%). The differences are small between regions in January, and they virtually disappear later in the winter with concurrent increase of soil moisture throughout the country (values >40% even in the northernmost part of the country).

Under the changing climate, the soil moisture in January increases especially in the north (Figs. 7B–7D). Later in the winter or in early spring, the soil moisture seems to decrease in the south but increase in the north. This tendency is the clearest in April, when the water from melting snow strongly determines the soil moisture. On the other hand, the soil moisture increases in October throughout the country towards the end of this century. In July, the soil moisture reduces slightly throughout the country along with the changing climate. Increasing temperature during growing season decreases soil moisture through its effect on evaporation. Increasing temperature outside growing season increases soil moisture through its impacts on increasing rainfall and snowmelt events. More details on the changes in soil moisture are given in Appendix 1 (Table A2), which shows the percentage increase/decrease for selected months under the changing climate throughout the country.

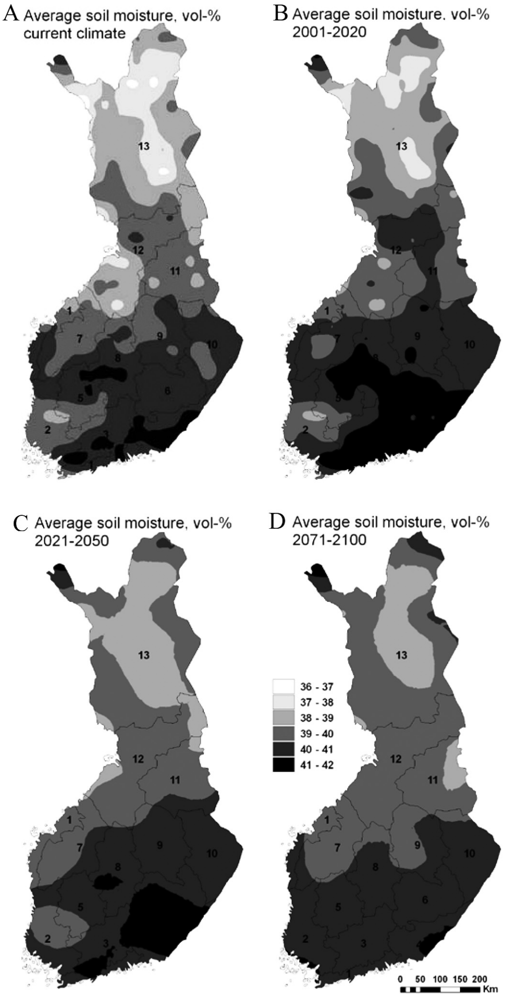

Fig. 7. Mean value of soil moisture (%) in January under the current climate (A) and under the changing climate in three time slices in the period 2001–2100 (B–D). See Fig. 4. for the numbers in the maps.

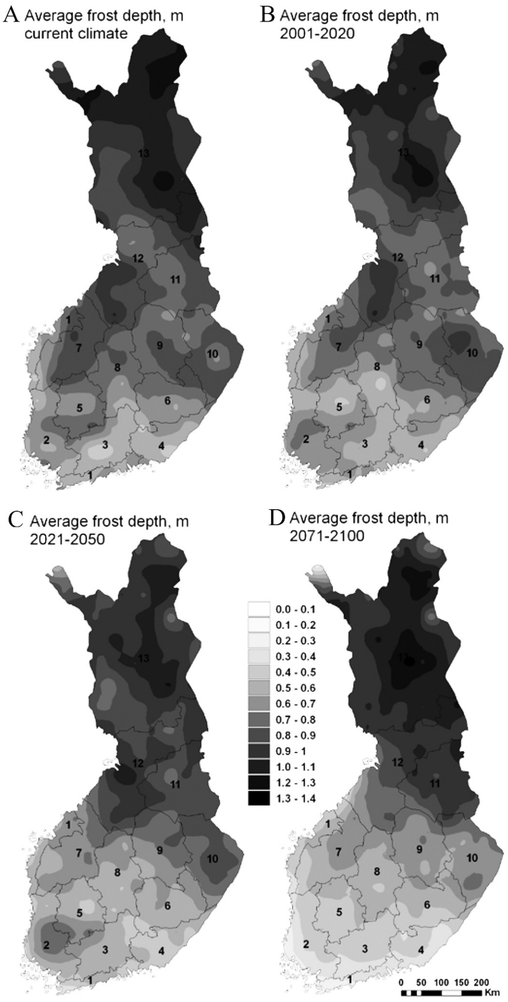

Fig. 8. Mean depth of soil frost cover (m) in January under the current climate and under the changing climate in three time slices in the period 2001–2100. See Fig. 4. for the numbers in the maps.

3.3 Soil Frost

Fig. 8A shows how the mean depth of soil frost varies throughout Finland, if the current climate is assumed. Following the general temperature pattern, the average depth of soil frost substantially exceeds 100 cm in large areas in northern and north-eastern parts of country. In the more southern areas, the mean depth of soil frost is smaller. In the most southern parts of the country it is only a few tens of centimetres. The mean value over the whole country is about 15 cm in November and 60 cm in April (Table 4). The spatial pattern holds also for the first (2001–2020) and second (2021–2050) calculation periods under the climate change (Figs. 8B–8D). But the depth of soil frost reduces by several tens of centimetres throughout the country. In the third calculation period (2071–2100), the soil frost nearly disappears in the southern and central parts of the coun-

Table 4. Mean depth of soil frost (cm) in each Forest Centre in selected months representing the main period of snow cover when the climate in the current climate (1971–2000) is assumed. In parenthesis, mean deviation.

Centre	November	February	April
Rannikko	6.4 (3.6)	86.6 (12.2)	38.1 (9.7)
Varsinais-Suomi	7.7 (4.2)	86.3 (13.5)	35.8 (6.8)
Häme-Uusimaa	8.4 (1.4)	81.5 (14.2)	40.4 (8.2)
Kaakkois-Suomi	7.7 (1.2)	79.1 (10.4)	41.2 (4.4)
Pirkanmaa	13.3 (2.0)	96.9 (14.4)	49.1 (6.5)
Etelä-Savo	12.3 (4.0)	92.7 (8.8)	51.0 (9.5)
Etelä-Pohjanmaa	15.5 (4.3)	102.5 (6.5)	61.0 (20.0)
Keski-Suomi	14.5 (3.3)	92.7 (7.4)	56.9 (6.2)
Pohjois-Savo	17.4 (2.1)	95.2 (5.3)	64.0 (5.2)
Pohjois-Karjala	20.2 (2.9)	101.4 (5.5)	72.7 (8.6)
Kainuu	21.8 (3.5)	102.1 (7.6)	86.3 (11.0)
Pohjois-Pohjanmaa	25.3 (4.5)	103.6 (10.3)	86.3 (19.8)
Lappi	35.8 (9.1)	120.0 (6.1)	116.4 (8.4)
Whole country	15.9 (3.5)	95.4 (9.4)	61.5 (9.6)

try, but in the northern parts the situation is partly opposite. Figure 8 shows, too, that in the first calculation period (2001–2020), the mean depth of soil frost falls slightly mainly in southern and central parts of the country. This is also the case for the second calculation period (2021–2050) indicating that the reduced snow cover increases the soil frost in some places even though there is a general increase in winter temperature. Similarly, the soil frost remains fairly deep in the northern part of the country in the third calculation period. On the other hand, in the northernmost part of the country, the depth of snow cover may locally even increase, because the increasing precipitation enhances snow accumulation more than the snow melting due to the shorter snow duration and higher temperatures.

Appendix 1 (Table A3) provides further details on how the climate change may affect the soil frost in selected winter months in different Forest Centres. Over the whole country, the mean depth of soil frost in February is about 5% lower in the first calculation period (2001–2020) than under the current climate. In November and March, the respective values are 18% and 32%, but the reduction varies substantially from Centre to Centre in such a way that the largest values are representative for the south and the smallest values for the north.

In the second calculation period (2021–2050), the depth of soil frost reduces further in southern and central Finland, up to the latitude 62°–63° N. Below this line, there is up to a threefold reduction compared to the first calculation period (2001–2020). On the other hand, above the latitude 62°–63° N, the depth of soil frost falls only slightly or even increases as is the case for the Pohjois-Pohjanmaa Forest Centre area. A similar pattern is also the case for November and April but in this case the reduction is substantially larger than in February. In the third calculation period (2071–2100), the depth of soil frost further reduces in February, but it still exists throughout the country. In this calculation period, the soil frost nearly disappears in southern and central parts of the country in November and April. Furthermore in northern Finland the reduction of soil frost increases substantially, though it still exists at the end of this century.

Fig. 9 presents the mean maximum values for the depth of the soil frost on a monthly basis for the selected Forest Centres. In the first (2001–2020) and second (2021–2050) calculation periods, the maximum values fall only slightly; mainly in early and late winter in southern and central parts of the country. In the third period (2071–2100), the maximum values fall substantially; again in the southern and central parts, but in the north

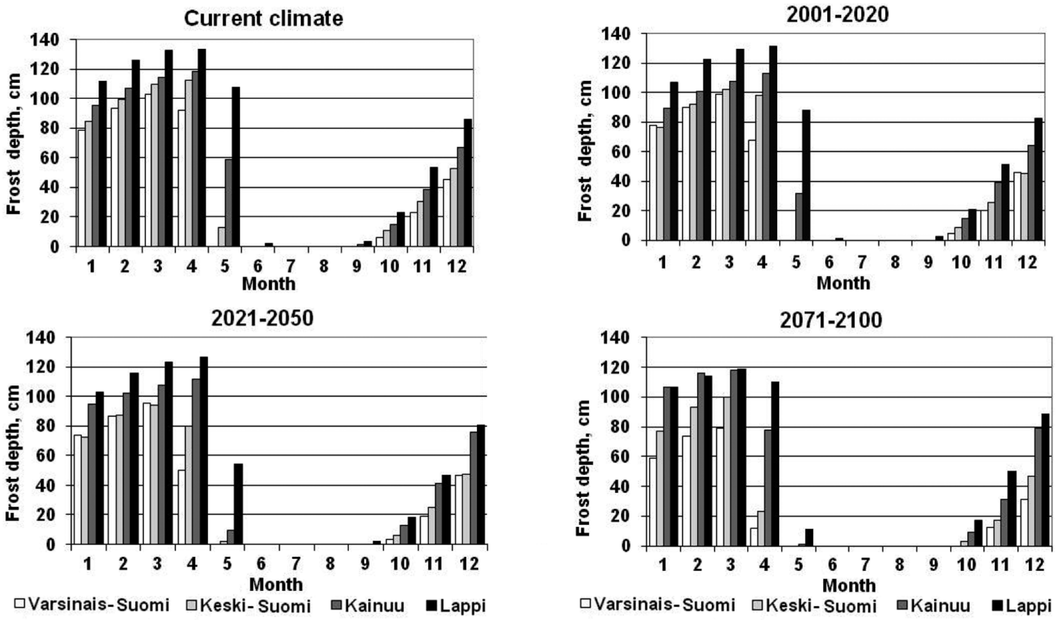

Fig. 9. Mean maximum depth of soil frost (cm) per moths in the selected Forest Centres representing the south–north gradient across Finland in different calculation periods.

they decrease only slightly. In these conditions, even in April the maximum values are close to those for the current climate.

Fig. 10 shows the occurrence of soil frost in the uppermost 10 cm in the soil profile in terms of the number of days with frozen soil per month. Under the current climate, the soil starts to freeze in late October, except the Lappi Forest Centre where the soil already freezes in late September. On the other hand, the soil frost disappears in April in the Forest Centres of Varsinais-Suomi and Keski-Suomi, whereas in May soil frost occurs in the Forest Centres of Kainuu and Lappi. This pattern holds also for the changing climate (Fig. 11) and the period with no soil frost may increase even in the northern Finland representing elongation both in spring and autumn. On the other hand, the number of days with soil frost in the deep winter (January through February) reduces only slightly in the southern and central parts of the country, and even increases slightly in the northern parts.

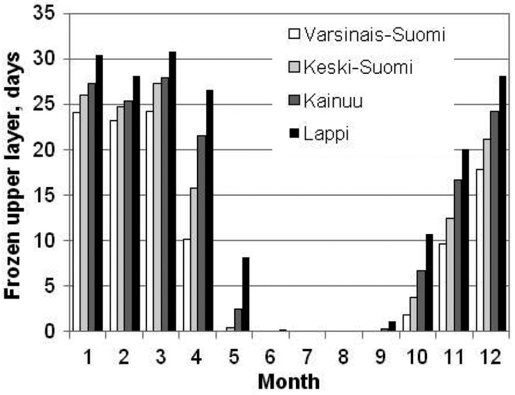

Fig. 10. Number of days with frozen upper layer (10 cm) of the soil profile under the current climate in the selected Forest Centres.

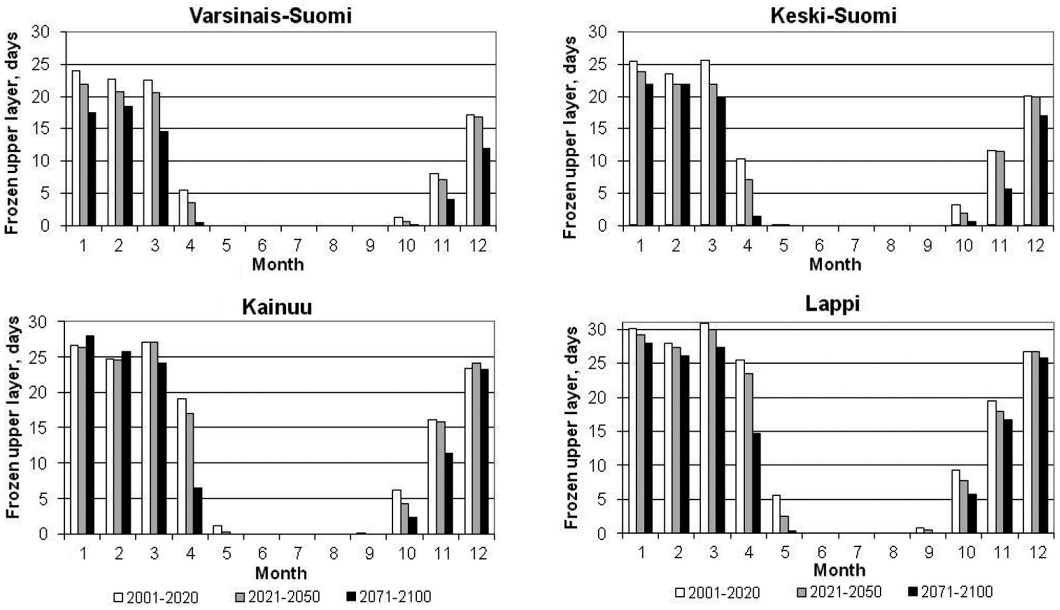

Fig. 11. Number of days with frozen upper layer (10 cm) of the soil profile under the changing climate in the selected Forest Centres.

4 Discussion and Conclusions

Increased precipitation and higher temperatures are expected to increase the forests' growth in the boreal conditions, such as in Finland (Kellomäki and Väisänen 1997, Nilson et al. 1999, Bergh et al. 2003, Kellomäki et al. 2007), even though the frequency of drought episodes may increase. However, the risk of windthrow of trees (Peltola et al. 1999) may increase through reduced tree anchorage due to a decrease in soil freezing between late autumn and early spring. In the above context, we studied how the climate change affects the accumulation of snow, soil moisture content and freezing of forest soil in the boreal conditions representing Finland (60°–70° N). The mode1 computations cover a period of 100 years, and were applied to sites with mineral soils without forest cover throughout the territory of Finland. The forest cover was excluded in the calculations in order to avoid the variability in the results, which are related to variability of thermal and moisture conditions on soil surface as affected by dynamics and development of forest stand due to climate and management and their effect on the incoming radiation and throughfall of water on the soil surface. Thus, if forest cover had included into simulations it would have interfered the interpretation of direct effects of climate variables during such a long simulation period than 100 years. However, it is well known that the depth of soil frost may be deeper on average in dense forest stands compared to sparse stands or in open area due to increased snow cover, but also depending on soil type and soil water content (e.g. Soveri and Varjo 1977, Solantie 1998)

The calculations were made using the ecosystem model developed by Kellomäki and Väisänen (1997) in which the selected weather and soil factors control the dynamics of forests. The model has been validated in several previous studies (Kellomäki and Väisänen 1997, Matala et al. 2003, 2005, Briceno-Elizondo et al. 2006). They show a high capacity of the model to simulate, in an acceptable way, the growth and development and the hydrological and thermal conditions in the forest soils typical for the Finnish forests (Venäläinen et al. 2001a, Laurén et al. 2005). This was also shown in the comparison between the simulated and measured values of maximum soil frost throughout Finland in this study.

In general, the snow cover is an integrated response to both temperature and precipitation (Solantie 2000), and there is a strong negative correlation between the air temperature and seasonal snow cover as employed in this study. IPCC (2001) reports widespread reductions in the snow cover throughout the 21st century, excluding increases at higher altitudes. By the end of this century, the Arctic Climate Impact Assessment (ACIA 2005) projects a 9–17% reduction in the annual mean snow cover in the Northern Hemisphere under the B2 scenario. In general, the snow accumulation season is projected to begin later, the melting season to begin earlier, and the fractional snow coverage to decrease during the snow season.

Our model calculations, regarding the snow duration, showed similar tendencies than those presented in ACIA (2005) and IPCC (2001); i.e. the climate change may substantially reduce the duration of snow cover throughout Finland, which represents the boreal zone at 60°N through 70°N. This finding is in line also with those by Peltola et al. (1999), Heikinheimo et al. (2001) and Venäläinen et al. (2001a). Furthermore, Kellomäki and Väisänen (1996) have found a fairly similar reduction in the duration of snow cover, when they applied the current model for a comparative analysis at a stand level between southern and northern Finland; i.e. snow cover would decrease throughout the country. But most prominently the decrease is found in the southern parts and coastal area of the Baltic Sea (e.g. Jaagus 1997). In the central parts of Finland (62°N), two thirds of the snow cover would be lost by the end of this century when applying the A2 scenario (Venäläinen et al. 2001a). The loss would be especially large in early and late winter as was also found in this study. Furthermore, according to our study, the snow melt seems to be in larger role for the decrease in snow cover in southern Finland than in northern Finland. In northern Finland, the snow cover is reduced more in early winter, implicating that larger share of the winter time precipitation may fall as rain compared to current climate.

The mean soil moisture tended to increase slightly in the first calculation period (2001–2020) but to reduce later. Regarding the seasonality, the soil moisture performed differently in different parts of the country. In late autumn (October) and deep winter (January), an increasing trend was evident regardless of the region. In early spring (April) and summer (July), the reducing soil moisture was evident in the southern and central parts of the country, whereas an increase was found in the northern part. The wintertime increase is due to the increased precipitation and replenishment of water from melting snow and soil frost. In spring time, the replenishment is reduced due to the less amount of water from melting snow compared to that available under the current climate. In summertime, the elevating temperature may enhance the evapotranspiration in such a way that it exceeds precipitation with a consequent increase of drought episodes, especially on soils with coarse fractions (Kellomäki et al. 2007).

The depth of frozen soil is related to the length of period with temperatures below 0°C. In the conditions with no snow cover, the depth of soil frost is linearly related to the frost sum (i.e. the sum of daily mean temperatures with value below 0°C) (Venäläinen et al. 2001a). On the other hand, snow cover slows the freezing of the soil due to the insulation. Thus, the effects of the climate change on the soil frost are related both to the temperature conditions and the accumulation of snow (or depth of snow cover), both of which are likely to change under the climate change.

Regarding the maximum depth of soil frost, our findings are well in line with those of Peltola et al. (1999), who found that the mean maximal soil frost in southern and central Finland would reduce from the current 100–150 cm to 50–100 cm under the climate change. In northern Finland, the reduction from the current 200–300 cm to 100–200 cm is expected. This implies that the current values in southern Finland would be applicable for northern Finland in the future which corresponds well with the findings by Venäläinen et al. (2001b). In Central and northern Finland, the probability of unfrozen soil would be less than that for southern Finland. In northern Finland, for example, the soil profile would be frozen in December even at the end of this century. Furthermore, Peltola et al. (1999) found that the duration of soil frost will decrease from 4–5 months to 2–3 months in southern Finland and from 5–6 months to 4–5 months in northern Finland, if a temperature elevation of 4°C is assumed.

The carrying capacity of the soil and the consequent trafficability of terrain is related to the snow accumulation, soil moisture and occurrence of soil frost and thus susceptible to impacts of climate change. The reduction in duration and accumulation of snow may reduce the carrying capacity of the soil, whereas increasing wetness of snow may compact and increase the snow density. More frequent melting-freezing episodes may increase the carrying capacity (e.g. Hyvärinen and Ahokas 1975) throughout Finland, excluding southern and coastal parts. In the future, the impacts of snow on the trafficability of terrain are probably the largest in northern Finland, where snow will persist even under the climate change. But its accumulation in a wetter form may increase in the near future, as indicated by the computations up to the year 2050.

The changes in snow cover may only slightly affect the trafficability of terrain compared to the effect due to increasing soil moisture and reducing soil frost. In general, increasing moisture reduces the carrying capacity of the soil. This is especially the case for soils with dominance of fine fractions whereas the dominance of coarse fractions reduces the effects of increasing moisture (e.g. Saarilahti 2002). One may expect that trafficability of forest soils from late autumn through late winter may reduce due to the increasing soil moisture mostly in southern Finland in the regions with much clay-rich soils. However, the impacts of the increasing soil moisture on the trafficability in winter time are decisively dependent on the occurrence and depth of soil frost. In this respect, the clear reduction of soil frost combined with the increasing soil moisture is likely to reduce the trafficability throughout Finland. This is the case especially in southern and central Finland, where the soil frost is greatly reduced along with increasing soil moisture. In the northern part of the country, the expected deterioration in trafficability may not be as drastic during the coming 50 years, but even in northern Finland the trafficability may be reduced by the end of this century.

As a conclusion, changing climate is expected to affect the existence of snow cover, soil moisture and soil frost throughout Finland. Regionally, quite large difference could be observed, as was reported in this study. These changes will affect both forest ecosystem functioning and also set challenges for wintertime timber harvesting.

Acknowledgements

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Appendix Table A1. Mean snow depth (cm) in December through March in the areas of different Forest Centres under the changing climate. In the parenthesis, % increase/decrease from that under the current climate (1971–2000).

Centre	Period	December	January	February	March
Rannikko	2001–2020	11.7 (–22)	22.0 (–19)	33.8 (–13)	24.9 (–19)
	2021–2050	10.2 (–35)	21.0 (–22)	29.0 (–26)	20.3 (–34)
	2071–2100	5.0 (–68)	9.3 (–66)	13.5 (–66)	6.2 (–80)
Varsinais-Suomi	2001–2020	14.3 (–19)	26.5 (–13)	39.5 (–8)	27.5 (–16)
	2021–2050	12.3 (–31)	25.7 (–15)	35.1 (–19)	23.4 (–28)
	2071–2100	6.3 (–65)	11.6 (–62)	17.3 (–60)	8.3 (–75)
Häme-Uusimaa	2001–2020	19.7 (–16)	34.8 (–10)	48.9 (–5)	38.2 (–8)
	2021–2050	16.7 (–29)	33.5 (–13)	43.0 (–17)	29.9 (–28)
	2071–2100	8.4 (–64)	15.3 (–61)	21.1 (–59)	10.7 (–74)
Kaakkois-Suomi	2001–2020	22.1 (–17)	37.3 (–10)	51.7 (–5)	41.7 (–8)
	2021–2050	20.2 (–24)	37.7 (–10)	48.3 (–12)	36.8 (–18)
	2071–2100	10.3 (–61)	18.4 (–56)	23.8 (–57)	12.6 (–72)
Pirkanmaa	2001–2020	21.8 (–14)	35.8 (–9)	49.8 (–4)	40.2 (–6)
	2021–2050	18.9 (–25)	35.9 (–9)	46.7 (–10)	33.4 (–22)
	2071–2100	9.3 (–63)	17.4 (–56)	24.0 (–54)	13.8 (–68)
Etelä-Savo	2001–2020	25.1 (–15)	40.6 (–8)	55.0 (–3)	44.0 (–6)
	2021–2050	22.9 (–22)	41.8 (–5)	52.9 (–7)	40.5 (–13)
	2071–2100	11.7 (–60)	22.5 (–49)	28.3 (–50)	16.0 (–66)
Etelä-Pohjanmaa	2001–2020	19.3 (–15)	30.1 (–10)	42.6 (–6)	32.4 (–10)
	2021–2050	17.1 (–25)	31.5 (–6)	41.4 (–8)	29.3 (–18)
	2071–2100	9.2 (–60)	17.0 (–49)	21.6 (–52)	11.8 (–67)
Keski-Suomi	2001–2020	25.8 (–13)	40.0 (–9)	54.2 (–5)	43.7 (–7)
	2021–2050	23.0 (–22)	40.9 (–7)	52.1 (–9)	40.0 (–15)
	2071–2100	11.8 (–60)	22.3 (–49)	28.0 (–51)	16.2 (–66)
Pohjois-Savo	2001–2020	29.6 (–11)	43.8 (–7)	58.2 (–4)	47.7 (–7)
	2021–2050	26.2 (–22)	45.2 (–4)	57.5 (–5)	47.8 (–7)
	2071–2100	13.6 (–59)	26.9 (–43)	34.3 (–43)	21.4 (–58)
Pohjois-Karjala	2001–2020	31.4 (–12)	47.5 (–7)	61.6 (–4)	51.8 (–6)
	2021–2050	28.8 (–19)	49.2 (–4)	60.9 (–5)	51.1 (–8)
	2071–2100	15.7 (–67)	29.7 (–57)	38.5 (–47)	24.0 (–55)
Kainuu	2001–2020	34.7 (–9)	49.5 (–4)	63.2 (–2)	55.3 (–2)
	2021–2050	30.3 (–21)	50.2 (–3)	63.5 (–2)	56.0 (–1)
	2071–2100	17.0 (–56)	32.3 (–38)	44.5 (–31)	32.0 (–44)
Pohjois-Pohjanmaa	2001–2020	31.1 (–10)	44.9 (–6)	59.0 (–3)	50.8 (–6)
	2021–2050	26.9 (–23)	45.3 (–5)	58.3 (–5)	50.7 (–6)
	2071–2100	15.9 (–54)	30.0 (–37)	40.1 (–34)	28.9 (–46)
Lappi	2001–2020	40.1 (–5)	53.1 (–1)	64.6 (+1)	59.4 (–1)
	2021–2050	37.0 (–12)	54.4 (+2)	66.9 (+5)	62.1 (+4)
	2071–2100	27.3 (–35)	43.5 (–19)	55.7 (–13)	48.3 (–19)
Whole country	2001–2020	25.1 (–14)	38.9 (–9)	52.5 (–5)	42.9 (–8)
	2021–2050	22.3 (–24)	39.4 (–8)	50.4 (–9)	40.1 (–15)
	2071–2100	12.4 (–59)	22.8 (–49)	30.1 (–47)	19.2 (–31)

Appendix Table A2. Mean changes (%) in the soil moisture compared to the soil moisture in the current climate (1971–2000) for different Forest Centres.

Centre	Period	January	April	July	October
Rannikko	2001–2020	1.80	0.32	–0.16	0.21
	2021–2050	1.07	–0.04	0.28	0.61
	2071–2100	2.33	–1.29	–0.65	0.57
Varsinais-Suomi	2001–2020	0.81	0.11	–0.55	0.11
	2021–2050	0.72	–0.13	–0.12	0.64
	2071–2100	1.91	–1.19	–1.53	0.62
Häme-Uusimaa	2001–2020	1.17	0.06	–0.36	0.07
	2021–2050	0.54	–0.78	0.04	0.99
	2071–2100	–0.03	–2.06	–0.46	1.06
Kaakkois-Suomi	2001–2020	0.76	0.40	–0.19	0.13
	2021–2050	0.35	–0.29	0.05	0.52
	2071–2100	0.00	–1.50	–0.86	0.66
Pirkanmaa	2001–2020	0.85	0.35	–0.32	0.07
	2021–2050	0.41	–0.25	–0.52	1.64
	2071–2100	–0.12	–1.15	–1.58	1.61
Etelä-Savo	2001–2020	1.33	0.36	–0.18	0.18
	2021–2050	1.09	–0.03	0.05	0.75
	2071–2100	–0.23	–1.02	–0.99	1.00
Etelä-Pohjanmaa	2001–2020	1.23	0.65	–0.28	0.27
	2021–2050	0.77	0.69	0.13	1.14
	2071–2100	0.67	0.54	–1.07	1.36
Keski-Suomi	2001–2020	1.44	0.63	–0.25	0.29
	2021–2050	1.08	0.47	–0.09	1.04
	2071–2100	–0.66	–0.45	–1.12	1.45
Pohjois-Savo	2001–2020	1.51	0.57	–0.14	0.22
	2021–2050	1.39	0.61	0.05	1.09
	2071–2100	0.01	0.16	–0.85	1.57
Pohjois-Karjala	2001–2020	1.17	0.60	–0.03	0.19
	2021–2050	1.16	0.76	0.17	0.94
	2071–2100	0.73	0.27	–0.58	1.43
Kainuu	2001–2020	1.31	0.66	–0.03	0.08
	2021–2050	0.58	0.83	–0.05	1.01
	2071–2100	–0.62	1.17	–0.74	1.47
Pohjois-Pohjanmaa	2001–2020	1.90	0.68	0.05	0.50
	2021–2050	1.03	1.10	0.14	1.40
	2071–2100	1.05	1.63	–0.66	1.89
Lappi	2001–2020	1.43	0.65	–0.01	0.63
	2021–2050	2.32	1.94	0.36	2.09
	2071–2100	2.93	2.73	–0.17	2.27
Whole country	2001–2020	1.28	0.46	–0.19	0.23
	2021–2050	0.96	0.38	0.04	1.06
	2071–2100	0.61	–0.17	–0.87	1.30

Appendix Table A3. Mean depth (cm) of soil frost in selected months in different Forest Centres under the changing climate. In the parenthesis, % increase/decrease from that under the current climate (1971–2000).

Centre	Period	November	February	April
Rannikko	2001–2020	4.2 (–33.7)	74.5 (–13.0)	18.0 (–52.6)
	2021–2050	3.4 (–46.3)	65.9 (–23.0)	11.0 (–71.1)
	2071–2100	1.4 (–77.9)	51.2 (–40.2)	1.4 (–96.3)
Varsinais-Suomi	2001–2020	6.1 (–21.2)	82.9 (–3.9)	19.5 (–45.4)
	2021–2050	5.0 (–34.9)	76.7 (–11.0)	11.4 (–68.1
	2071–2100	2.4 (–69.4)	59.2 (–31.4)	1.2 (–96.8)
Häme-Uusimaa	2001–2020	7.0 (–16.2	80.1 (–1.6)	24.3 (–39.7)
	2021–2050	5.6 (–32.7)	75.2 (–7.7)	11.9 (–70.5)
	2071–2100	3.0 (–64.3)	66.4 (–18.5)	1.0 (–97.5)
Kaakkois-Suomi	2001–2020	6.1 (–21.5)	74.8 (–5.4)	26.0 (–37.1)
	2021–2050	5.8 (–25.6)	66.6 (–15.8)	13.5 (–67.2)
	2071–2100	2.6 (–66.9)	62.3 (–21.2)	0.9 (–97.8)
Pirkanmaa	2001–2020	9.9 (–25.7)	83.2 (–14.2)	31.7 (–35.5)
	2021–2050	7.8 (–41.3)	78.2 (–19.4)	16.0 (–67.5)
	2071–2100	3.7 (–72.5)	73.3 (–24.4)	3.0 (–93.9)
Etelä-Savo	2001–2020	9.8 (–20.6)	90.2 (–2.7)	35.8 (–29.8)
	2021–2050	7.9 (–35.8)	78.5 (–15.3)	19.3 (–62.5)
	2071–2100	3.5 (–71.4)	74.4 (–19.7)	2.8 (–94.4)
Etelä-Pohjanmaa	2001–2020	11.6 (–25.5)	97.0 (–5.4)	38.3 (–37.1)
	2021–2050	9.1 (–41.4)	86.0 (–16.1)	24.7 (–59.6)
	2071–2100	4.2 (–73.0)	77.0 (–24.9)	5.5 (–90.9)
Keski-Suomi	2001–2020	10.9 (–24.5)	84.9 (–8.4)	35.3 (–37.9)
	2021–2050	9.3 (–35.6)	80.3 (–13.4)	22.6 (–60.3)
	2071–2100	4.1 (–71.7)	77.5 (–16.4)	4.0 (–92.9)
Pohjois-Savo	2001–2020	14.8 (–15.0)	95.2 (0.0)	46.9 (–26.6)
	2021–2050	12.8 (–26.0)	92.0 (–3.3)	34.6 (–45.9)
	2071–2100	5.2 (–70.1)	85.8 (–9.9)	7.4 (–88.5)
Pohjois-Karjala	2001–2020	17.9 (–11.5)	100.4 (–1.0)	55.0 (–24.3)
	2021–2050	14.7 (–27.4)	94.6 (–6.7)	40.1 (–44.8)
	2071–2100	6.5 (–67.6)	87.5 (–13.7)	7.2 (–90.1)
Kainuu	2001–2020	21.3 (–2.4)	96.5 (–6.4)	71.2 (–17.4)
	2021–2050	20.1 (–7.7)	98.7 (–3.3)	64.3 (–25.5)
	2071–2100	12.5 (–42.5)	111.0 (+8.8)	21.8 (–74.7)
Pohjois-Pohjanmaa	2001–2020	22.5 (–11.1)	101.8 (–1.7)	68.4 (–20.8)
	2021–2050	20.1 (–20.5)	106.5 (+2.7)	58.6 (–32.1)
	2071–2100	12.5 (–50.5)	103.3 (–0.3)	21.3 (–75.3)
Lappi	2001–2020	33.1 (–7.4)	115.6 (–3.7)	108.8 (–6.5)
	2021–2050	27.0 (–24.5)	109.8 (–8.5)	98.0 (–15.8)
	2071–2100	26.5 (–25.8)	110.5 (–8.0)	55.7 (–52.2)
Whole country	2001–2020	13.5 (–18.2)	90.5 (–5.2)	44.6 (–31.6)
	2021–2050	11.4 (–30.7)	85.3 (–10.8)	32.8 (–53.1)
	2071–2100	6.8 (–63.4)	80.0 (–16.9)	10.2 (–87.8)