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Feedback processes between climate, surface and vegetation at the northern climatological tree-line (Finnish Lapland)

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In northern ecosystems near the climatological timberline, the interactions between vegetation and disturbances, such as forest fire, are particularly important, as the changes in vegetation may produce large feedbacks into the climate. The changed climate and the altered surface conditions may in turn prevent the vegetation from returning to its original state. The effect of fire on local climate and its implications for forest regeneration were studied in the Tuntsa area of Finnish Lapland that was affected by a widespread forest fire in 1960. Direct measurements were applied for determining the variation of climate parameters in a spruce-covered fire refuge and on the treeless tundra environment resulting from the fire. The annual and seasonal dynamics of heat and water fluxes, snow conditions and radiation processes were simulated using an SVAT model known as COUP. Fire-induced deforestation increased the wind velocity by 60%, changed the soil thermal regime through a 20–30 cm reduced snow cover, lowered the evapotranspiration and diminished the Bowen ratio to 0.4. The resulting severe local climate is probably one of the precluding factors in the recovery of the forest in this sensitive region.

Introduction

The development and the structure of natural vegetation in northern ecosystems are primarily controlled by the climate and climate-related external disturbances (Arseneault and Payette 1992). The climate-disturbances–vegetation interactions are particularly important at high latitudes, where vegetation change may involve a feedback to climate that may in turn prevent the vegetation from returning to its original state (Bonan *et al*. 1992, Lynch *et al*. 1999).

Fire is one of the dominant forms of disturbance in the boreal forest and in the transition zone between forest and tundra (Kasischke and Stocks 2000). Fires destroy all kinds of ground vegetation as well as timber, bringing about severe soil erosion. Furthermore, the changed vegetation of the forest, the forest–tundra ecotone may cause a large feedback to climate (Chapin *et al*. 2000, Rupp *et al*. 2002). The local climate of the burned area differs markedly from that of the forest interior. The altered near-surface environment can significantly affect regional albedo and regional warming (Bonan *et al*. 1992), and exhibit more extreme surface and soil temperatures, lower humidity, increased wind speed (Carlson and Groot 1997), thinner snow cover (A. Vajda *et al*. unpubl. data) and lower evaporation when compared with the forest. The reduced snow depth promotes frost disturbances in the soil profile (Arseneault and Payette 1992) and the occurrence of late spring frost. In addition, the lack of snow in open areas may cause a lack of sufficient humidity for some types of plants. Finally, the changed climate and the soil patterns can have a strong influence on the forest regeneration at the northern climatological timberline. Efforts to establish the original vegetation on the fire-disturbed area or in large, clear-cut forest openings in the boreal forest often fail (Carlson and Groot 1997). The transformation of areas from forest to tundra communities as a result of fire-related damage to tree populations has been reported from Canada (Sirois and Payette 1991), northern Sweden (Zackrisson 1977) and Siberia (Tyrtikov 1978 as quoted by Sirois and Payette 1991).

Several studies have been made concerning the changes in the small-scale spatial variation of climate on fire-induced clearings and the impact of the changed regional climate on the recovery of the initial forest vegetation in boreal and subarctic sites. Most of the previous studies have focused on the ecological consequences of the fire-induced deforestation, the effects of these on habitat variability and post-fire vegetation recovery at the arctic tree-line (Sirois and Payette 1991, Arsenault and Payette 1992, 1997, Landhausser and Wein 1993, Arseneault 2001, Kauhanen 2002). According to these, under favourable climatic conditions, post-fire recruitment may induce an abundant regeneration (Landhausser and Wein 1993, Lampainen *et al.* 2004), even triggering the invasion of deciduous trees and tall shrubs into the burned tundra vegetation. However, many studies have reported changes from a boreal to an arctic landscape as the result of post-fire degradation and the disappearance of the conifer stands at the tree-line. Through deforestation the climatic conditions on the studied sites became more unfavourable, reducing the snow depth and thus the protection of snow cover, increasing frost disturbances (Arsenault and Payette 1997), inducing water stress that lowers tree productivity (Sirois and Payette 1991).

Furthermore, the timberline patterns in northern Fennoscandia are mainly shaped by the interaction between climate and grazing (Oksanen *et al.* 1995). In Finnish Lapland, large timberline areas are subjected to relatively intense summer grazing by reindeer. Reindeer browsing on small birch twigs strongly affects plant growth and reproduction, reducing significantly the height of the growth and the shoot length, and accelerating the dieback of shoots, e.g. in the case of willow by 50%. The growth and survival of juvenile plants are distinctively more affected, as reindeer feed more heavily on young plants (den Herder 2003). On the other hand, reindeer avoid forests in summer, due to mosquitos, and prefer areas covered with small vegetation.

There exist a number of studies dealing with the modelling of responses of ecosystems to disturbances and the subsequent feedbacks between climate and the biosphere in the boreal and subarctic zone (Rupp *et al.* 2000, He *et al.* 2002, Chapin *et al.* 2003). The simulations made using various models — such as ALFRESCO and LANDIS — indicate an increased fire regime under future warming conditions; together with forest harvesting, these conditions accelerate the decline of boreal tree species and create considerable changes in landscape patterns, which may have further implications for climate-disturbance–vegetation interactions.

The objective of the current study is to examine how human activities, such as forest fires, harvesting and reindeer grazing, impact the climate on the local scale and thereby accelerate the alteration of surface and vegetation in a sensitive environment near the climatological borderline of forest, in the Tuntsa area of Finnish Lapland. The analysis is based on field measurements in, and simulations concerning, the Tuntsa area, affected by a widespread forest fire in 1960. Following the fire, the reforestation has not succeeded well; a substantial area is still unforested and it is probable that after the fire the local climatological conditions have become more unfavourable. Naturally there are other reasons which might exacerbate the poor regeneration, such as: the poor quality of the soil, as the area is a barren watershed, the complete excision of the damaged trees, the partly southern origin of the planting material and the use of a growth hormone for disinfection during one summer, which killed sprouting (Haataja 1993). The post-fire heat and water fluxes in the soil, snow conditions, evaporation and radiation processes were estimated using the COUP model (Coupled heat and mass transfer model for soil–plant–atmosphere system) described by Jansson and Karlberg (2001).

The intention of our study is to provide new information about the feedback mechanisms between the atmosphere and the surface in the sensitive region near the climatological borderline of forests. The study may provide useful information for the ecologist and forestry research concerning the re-establishment of forest in deforested areas.

Material and methods

Study area

The Tuntsa area is located in eastern Finnish Lapland between 67°30´N, 29°30´E and 67°45´N, 30°E (Fig. 1). The bedrock is composed of Archaean mafic volcanites, amphibolites and metasediments, and the hilly glaciated terrain reaches 300–475 m a.s.l. A major part (80%) of the parent soil materials are tills superimposed on the bedrock as a 0.2–2 m thick veneer. Stratified sand and gravel deposits occur in the river valleys. The fine fraction of the tills varies between 25% and 36%; the Podzol (Spodosol) was classified as a Typic Haplocryod. A detailed description of the regional climate of the area has been published by Vajda and Venäläinen (2003).

In 1960 19 882 ha of vegetation was destroyed in the Tuntsa forest fire, of which 9307 ha was virgin forest, 5051 ha dwarf trees (krummholz) and 5524 ha was a treeless area (Haataja 1993). Prior to the fire the area was covered by mature (> 150 yrs) Norway spruce (*Picea abies*) forest intermixed with downy birch (*Betula pubescent*), but with Scots pine (*Pinus silvestris*) dominating the stratified sand and gravel deposits in the river valleys. The fire was widespread, but fire refuges, comprising stands dominated by spruce, were left in moist sites and in swales up to the tree-line (i.e. 460 m a.s.l.). After the fire, the major part of the damaged trees was harvested — a total of 275 000 m^3 (Haataja 1993). The area was regenerated from 1961 onwards with Scots pine by seeding and later, until 1976, by planting and mechanical site preparation. Despite a good start, the regeneration with pines failed on sites formerly covered by spruce. The natural regeneration of birch has been hampered by intensive reindeer grazing. The grazing pressure in winter and the trampling in summer may cause severe reduction or even removal of the vegetational structure in a sensitive arctic environment (Virtanen 2000, Cooper and Wookey 2003). Large areas are now treeless, having tundra-like vegetation, formed mainly by lichens, mosses and dwarfed shrubs, with some patterned ground features.

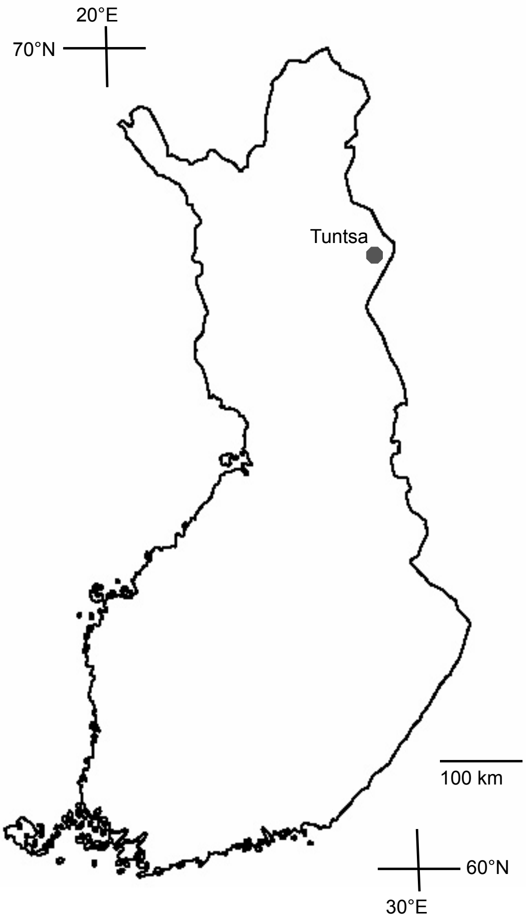

Fig. 1. Location of the study site in Lapland, northern Finland.

Measurements, model description and applications

Field measurements

In order to ascertain the present local clima-

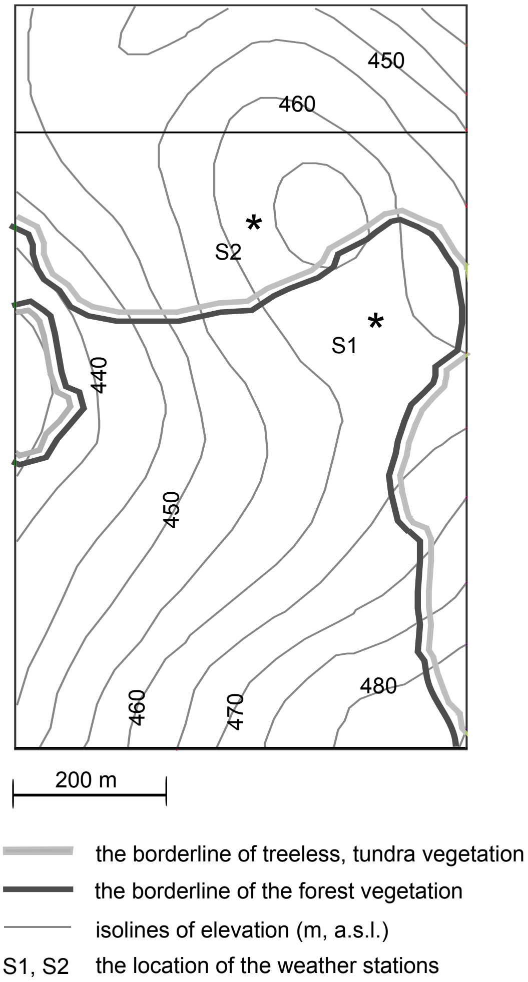

Fig. 2. The topographic map and the surface roughness of the area studied, and the location of the weather stations.

tological conditions in the affected area, two sites were selected in early September 2003 for detailed meteorological measurements (Fig. 2). The sites were chosen on the basis of having similar elevation, slope and soil characteristics, and as being locations where snow depth and density measurements had been earlier carried out, in March 2003 (A. Vajda *et al*. unpubl. data). The two automatic weather stations were installed close to each other: one of them situated in the forest, surrounded by Norway spruce (67°38´20´´N, 29°51´57´´E, 462 m), the other one on a burned open site covered by short tundra vegetation (67°38´26´´N, 29°51´45´´E, 464 m). The average, maximum and minimum air temperatures, pressure, relative humidity, global solar radiation, wind speed and direction and the amount of precipitation were measured hourly from 9 September 2003 to 20 September 2004. The wind sensors were situated at an elevation of 3 m, the other sensors at an elevation of 2 m. The soil temperature and soil moisture were measured, as well as the temperature at three depths (0.1 m, 0.3 m and 0.5 m) and the soil water content at 0.1 m. The sensors of global radiation and wind speed had been damaged during winter, most probably because of the frost and extreme weather conditions. A gap in precipitation measurement occurred during the frost season (November–early April), when the sensors were not able to record snowfall.

Model description

An estimation of the annual and seasonal dynamics of the post-fire heat and water fluxes in the soil, evaporation, snow conditions and radiation processes was carried out with the COUP model, developed by the Swedish Royal Institute of Technology, Department of Land and Water Resources Engineering. A complete technical description of the model including equations and settings can be found on the internet (http://www.lwr.kth.se/coup.htm). The model has had a number of previous applications concerning the water and heat balance for different vegetation cover, forest stands, crops and bare soils (Lewan 1993, Gärdenäs and Jansson 1995, Persson 1997, Jansson *et al*. 1999, Gustafsson *et al*. 2004). The one-dimensional simulation model is based on the energy balance approach, and simulates the water and heat balance of a vertical soil profile divided into a finite number of horizontal layers. The transport equations are formulated as the combination of a balance equation with a flux equation, and are solved by numerical integration with a finite-difference method. The equation of water flow is solved by combining Darcy's law and the law of conservation of mass. Heat flow is described in an analogous way by combining Fourier's law and the law of energy conservation. Evapotranspiration is calculated using the combined Penman-Monteith equation. The COUP model contains numerous options by which the user can define which processes to include in the simulation, e.g., heat and water flow, nitrogen and carbon processes, snow pack, vegetation, evaporation, irrigation, etc.

Meteorological data are used as the forcing in the simulation and are given as measured or parameter values. The soil and plant properties are represented as parameters. The soil heat and water characteristics for each soil layer as well as the hydraulic conductivity must be defined to solve the equation. The parameters requested to describe the influence of the vegetation are leaf area index, albedo, stand height and root depth. As the total storage of plant-available water is mainly influenced by root depth, the water uptake by roots is described by defining the proportional distribution of roots among the soil layers.

Input parameters for the model

The parameters needed as input in the modelling are based on site measurements, literature values and calibrations against the available observations of soil temperature and moisture content. Previous estimates of soil properties suggest a sandy soil (to a depth of 3.5 m). Based on this sample, a 0.85 m deep sandy forest soil profile with a thin organic layer was selected from the database of the model for the simulations. The spruce stand and short vegetation parameters were defined based on the literature and on-site observations. As the forest site is covered by a sparse spruce stand intermixed with rich ground vegetation, the leaf area index (LAI) was considered to be 4–4.5 $m^2 m^{-2}$. The stand height was set to 9 m and the root depth to 30 cm. For the short tundra vegetation the stand parameters were adjusted to 0.5–1 $m^2 m^{-2}$ for LAI, to 30 cm for root depth and to 10–20 cm for height. The model was validated against the measured hourly soil temperature and water content data over a 3-week period by comparing the modelled values with the measurements.

Model applications

The model was run for the two sites with different surface properties with daily meteorological data measured on the sites for the available measurement period (September 2003–September 2004). The global radiation, mean temperature, wind speed, precipitation and relative humidity were used as driving variables. Since the model does not take into account the drifting of the snow, a significant factor on an open site, the amount of winter precipitation for the open site was reduced by 30% based on the snow measurements and analysis from March 2003. The simulated heat and water fluxes were compared and statistically analyzed.

The simulations were also run with 28-year (1975–2003) driving datasets for forest and tundra vegetation. Since meteorological measurements have not been made in the study area for the mentioned period, the corresponding measurements from representative stations were used. The air temperature, relative humidity and precipitation data were applied from the closest meteorological station at Salla Värriötunturi (67°45´N, 29°37´E, 370 m a.s.l.), while the global radiation data were taken from the Sodankylä Research Centre (67°22´N, 26°37´E, 179 m a.s.l.). For the determination of wind data, wind measurements from two stations with roughly similar geographical locations, elevations and surroundings were selected: for tundra vegetation the data from Kuusamo Airport (65°59´N, 29°13´E, 264 m a.s.l.) and for spruce forest the Sodankylä Research Centre (67°22´N, 26°37´E, 179 m a.s.l.). Based on these measurement data-sets we calculated the wind speed for the two different surfaces using the logarithmic wind profile:

$$u_z = \frac{u_*}{k} \ln\left(\frac{z}{z_0}\right)$$

where u_z is the wind speed at elevation z above the surface, k is the von Kármán constant, u_* is the friction velocity and z_0 the surface roughness length.

In addition to the long-term simulations, we tried to reproduce the pre-fire and post-fire local climate of the study area for the case of a possible forest fire during the simulation period. First, we ran the model with the surface properties and meteorological data specific to the spruce forest (1975–June 1980), after which the forest vegetation was replaced with the surface properties of a burned site (July 1980–May 1982) and then

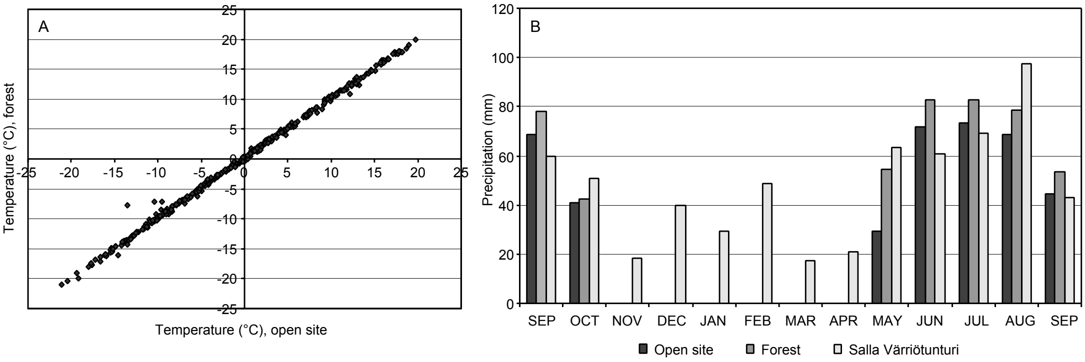

Fig. 3. Comparison of (**A**) mean air temperature and (**B**) the monthly amount of precipitation over the tundra vegetation (at the height of 464 m) and forest (at the height of 462 m) during the period 9 September 2003–20 September 2004.

with the post-fire tundra vegetation and the corresponding driving data (June 1982–2003).

Results

Comparison of the observed local climate at the two sites

The mean, minimum and maximum air temperature, relative humidity, precipitation, soil temperature and water content measured on the open site covered by tundra vegetation and in the forest were analyzed in detail. As the sensors of global radiation and wind speed had been damaged during the winter, the variation of these parameters was analyzed for autumn 2003.

The variation of daily mean air temperature was about the same over the two sites (Fig. 3), with a value of 1 for the linear regression coefficient. The annual mean temperature in the forest was –0.2 °C and –0.4 °C on the open site. Similar features characterize the variation of daily maximum and minimum temperatures (Table 1). Since the maximum and minimum air temperatures during the season may influence plant regeneration, these parameters have been compared for the two sites. At Tuntsa the length of the growing season is 77 days, starting around 20 June and ending about 25 August (Vajda and Venäläinen 2003). The average daily minimum temperature was similar on both sites (8.9 °C in the forest, 9.2 °C on the open site); the average daily maximum temperature was higher by only 1 °C in the forest as compared with that in the open area. The relative humidity had a similar variation at the two stations for the whole measurement period (correlation coef-

Table 1. Comparison of parameters measured in a spruce forest and on treeless tundra vegetation.

	Correlation coefficient	RMS error	Linear regr. coefficient
Mean air temperature	1.00	0.46	1.00
Minimum air temperature	1.00	0.75	0.99
Maximum air temperature	1.00	0.79	0.99
Global radiation	0.98	162.95	0.96
Relative humidity	0.99	1.73	0.98
Wind speed	0.69	1.45	0.46
Precipitation	0.87	1.43	0.75
Soil temperature at 10 cm	0.99	0.58	0.99
Soil temperature at 30 cm	0.99	0.51	0.99
Soil temperature at 50 cm	0.99	0.56	0.98
Soil moisture at 10 cm	0.73	4.84	0.53

ficient 0.99, linear regression coefficient 0.98); however, during the warm season, the relative humidity was higher by 1%–5% in the forest as compared with that at the open site. The forest was usually moister than the tundra, the monthly amount of precipitation exceeding that measured on the open site by 10%–15% (Fig. 3). The total amount of precipitation registered over the whole measurement period, except for the frost season, was 397.4 mm at the open site and 472.2 mm in the forest. During the autumn the mean daily wind speed recorded at 3 m above ground level ranged from 0 to 7 m s^{-1}. In the open area the low vegetation allowed a higher wind velocity — a mean wind speed of 3.7 m s^{-1} — than in the forest, where the mean wind speed during the autumn was 1.2 m s^{-1}. Comparing the simultaneous global radiation data from the two weather stations, the daily amount of radiation at the open site exceeded the values measured in the forest by 25%. As the experiment sites are situated close to each other, this difference in the measured radiation values must be produced by the shading effect of the forest canopy.

The variation in the soil temperatures (at depths of 0.1, 0.3, 0.5 m) certifies the remarkable influence of the surface conditions (Fig. 4). The mean daily soil temperature at a depth of 0.1 m — which reflects most effectively the impact of the surface conditions — oscillates over a wider range at the open site than in the forest (Table 2), with a mean temperature of 2.9 °C under the shrub and grass vegetation and 3.4 °C under the spruce trees. Soil temperatures were higher at the open site during summer as compared with those in the forest, while this trend was reversed during the winter, when the soil frost occurred earlier and was more intense at the open site than in the forest. The cumulative soil temperature above 5 °C during the growing season was higher by 30–60 °C d at the open site than in the forest (Table 2).

At the open site the soil at a depth of 0.1 m was moister (annual mean 18.3%) than in the forest (annual mean 15.4%) except in November and December, due to the dislocation of the soil frost in the forest. The variation of the daily soil water content exhibits the accentuated receptiveness of the soil moisture to the air temperature variations at the open site, especially during the

Table 2. Variation of soil temperature and water content at the study site.

	Annual (Sept. 2003–Sept. 2004)												Growing season			
	Soil temp. 0.1 m (°C)			Soil temp. 0.3 m (°C)			Soil temp. 0.5 m (°C)			Soil water content 0.1 m (%)			Cumulative soil temp. (°Cd)			Av. soil moist. (%)
	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	0.1 m	0.3 m	0.5 m	0.1 m
Tundra	2.9	15.3	−2.2	2.8	13.6	−0.9	2.9	12.4	−0.1	18.3	41.7	10.1	464.4	374.9	311.6	22.3
Forest	3.4	14.1	−0.1	3.4	12.3	0.2	3.2	10.7	0.1	15.4	37.9	8.7	433.7	341.9	257.6	18.2

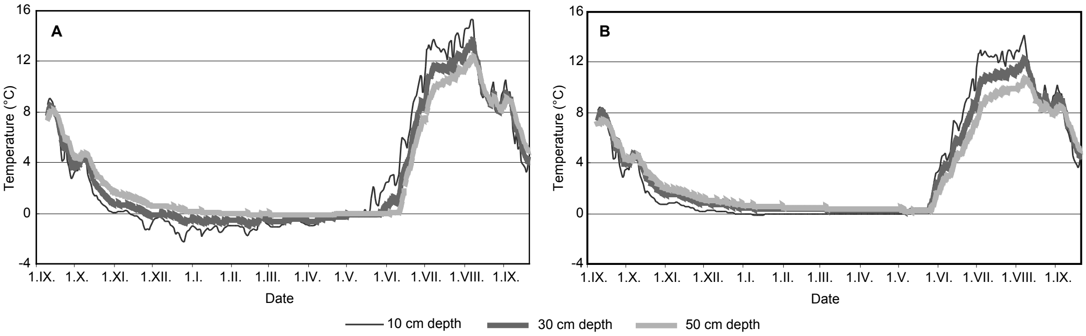

Fig. 4. The variation of mean soil temperature at depths of 10 cm, 30 cm and 50 cm (**A**) beneath the tundra vegetation and (**B**) in the forest during the period 9 September 2003–20 September 2004.

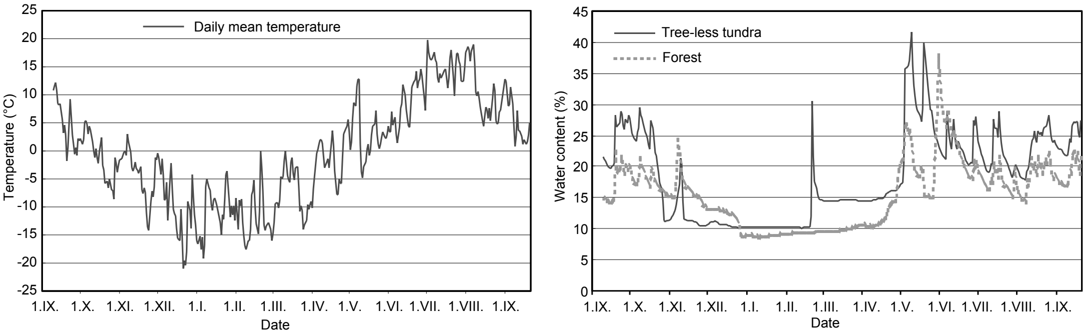

Fig. 5. The mean daily air temperature and soil moisture at a depth of 10 cm during the period 9 September 2003–20 September 2004.

cold season, when an increase in air temperature meant a considerable rise in soil moisture (Fig. 5). The peak in the soil water content level occurred in spring, at the time of the snowmelt, with a time lag of 20 days in the spruce forest.

Simulated heat and water fluxes

The COUP model reproduced reasonably well the observed annual variation in soil temperature in each layer, the coefficient of determination exceeding 0.93 when modelling the climate for tundra vegetation and 0.88 in the case of the forest. However, a slight overestimation of the wintertime soil temperature and underestimation of the summertime soil temperature (0.3–2 °C) occurred in all simulations (Fig. 6). According to the simulations, the soil surface temperature at the site covered with short vegetation had a more pronounced fluctuation (between –9.1 °C and 21 °C) during the simulated period than in the forest (between –4.8 °C and 16.7 °C). The depth of snow cover was effectively reproduced by the COUP model, the simulated patterns of snow cover basically coinciding with those measured during the preceding winter (A. Vajda *et al.* unpubl. data). Due to the snow drifting at the open site, the maximum depth of snow cover was 30 cm smaller there (0.64 m) than in the forest (0.96 m); for these depths the corresponding water equivalent was 119.3 mm (on the short vegetation) and 183.4 mm (in the forest).

The soil water content was deficiently described by the model; the coefficients of determinations were rather low: 0.74 for the open site and 0.49 for the forest. The annual variation of soil moisture was analysed for the 5–10 cm layer, the 25–30 cm layer and the 40–60 cm layer (Fig. 7), similarly to the soil temperature analysis. According to the simulations the monthly average of soil water content in the forest was higher

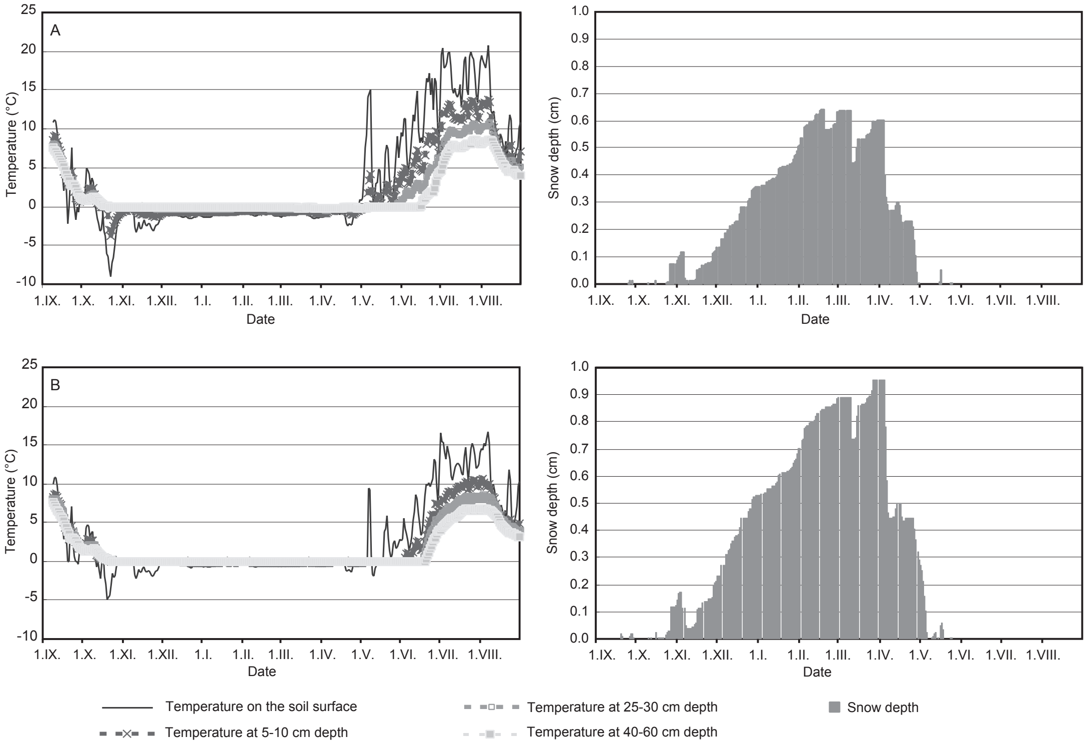

Fig. 6. The simulated mean soil temperature and snow depth for (**A**) the tundra vegetation and (**B**) the forest, September 2003–August 2004.

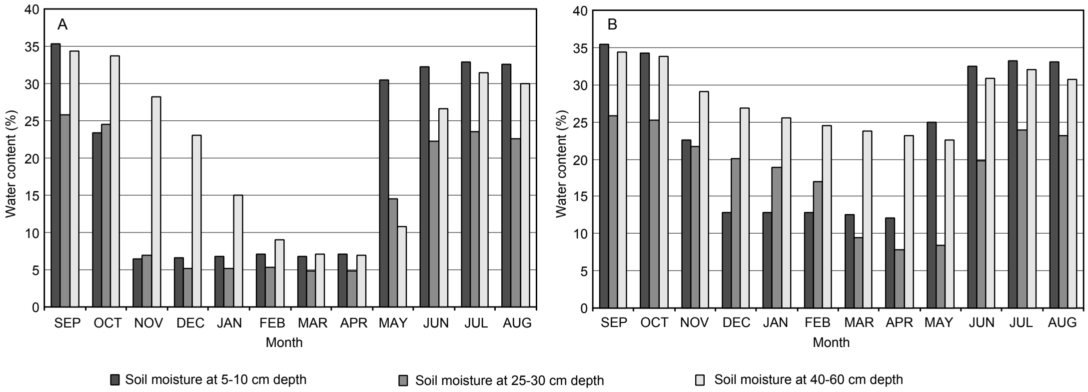

Fig. 7. Simulated soil water content at depths of 5–60 cm for (**A**) the tundra vegetation and (**B**) the forest, September 2003–August 2004.

during the whole year however the differences were less during the summer. An exception to the general variation occurred in May, when the earlier snow melt at the open site assured a significant supply of water for the soil there. The simulations contradict the results of measurements at a depth of 0.1 m. The discrepancy may be caused by the differing sand fraction of the soil profiles at the depth mentioned. The sand content of the forest soil is 15% higher than that of the open site, permitting a faster infiltration of water. The soil structures at other depths were similar for the two sites. Taking into account the mainly similar soil properties of the soil profiles we decided

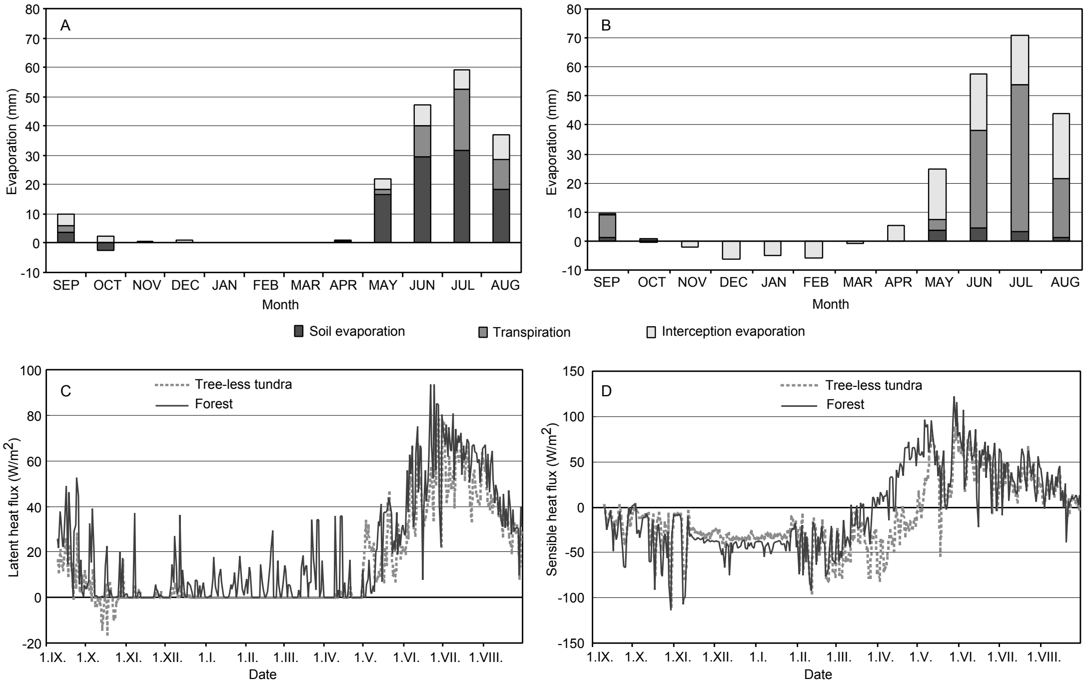

Fig. 8. The simulated monthly mean evaporation and its components for (**A**) the tundra vegetation and (**B**) the forest; (**C**) the latent heat and (**D**) sensible heat fluxes at the two sites (tundra and forest).

to use a single corresponding soil profile from the model's data base for our simulations. This indeed indicates that the detailed soil or vegetation properties may be of significant importance in the soil moisture description.

Comparison of the two vegetation types in terms of their mean evaporation during the warm season (May–August) shows that the spruce forest had a higher value (1.62 mm day^{-1}) than the tundra vegetation (1.35 mm day^{-1}). In the variation of monthly evaporation, the values from the forest constantly exceeded those of the short vegetation (Fig. 8). At both sites the evaporation reached its maximum in July, when the water availability, global radiation and the leaf area index have their highest values. With respect to the components of evaporation, the soil evaporation was higher over the tundra vegetation (20–30 mm month^{-1}), while in the forest the transpiration and interception evaporation were the main components (together 60–70 mm month^{-1}) of the total evaporation, as the components of evaporation are controlled by the LAI of the vegetation, the surface resistance and the interception storage. The seasonal patterns in the latent heat flux from the open site and the forest are mainly determined by the evaporation. The latent heat flux from the forest was higher than from the open site during almost the whole year, except for the first part of May, when the snow cover still persisted in the forest.

During the warm season the sensible heat flux from the forest exceeded that from the open site. The winter was characterized by a downward sensible heat flux over both sites (Fig. 8), with a larger net loss of latent heat from the forest during November–January. Furthermore the daily average of sensible heat flux over the forest increased to positive values during April, when the tree canopies are already snow-free; thus the sensible heat flux is then larger from the trees than from the still snow-covered tundra.

Long-term (28-year) simulations

The simulated long-term soil temperatures showed the typical differences between the two sites, especially during the warm season (Fig. 9). The annual temperature amplitude at the

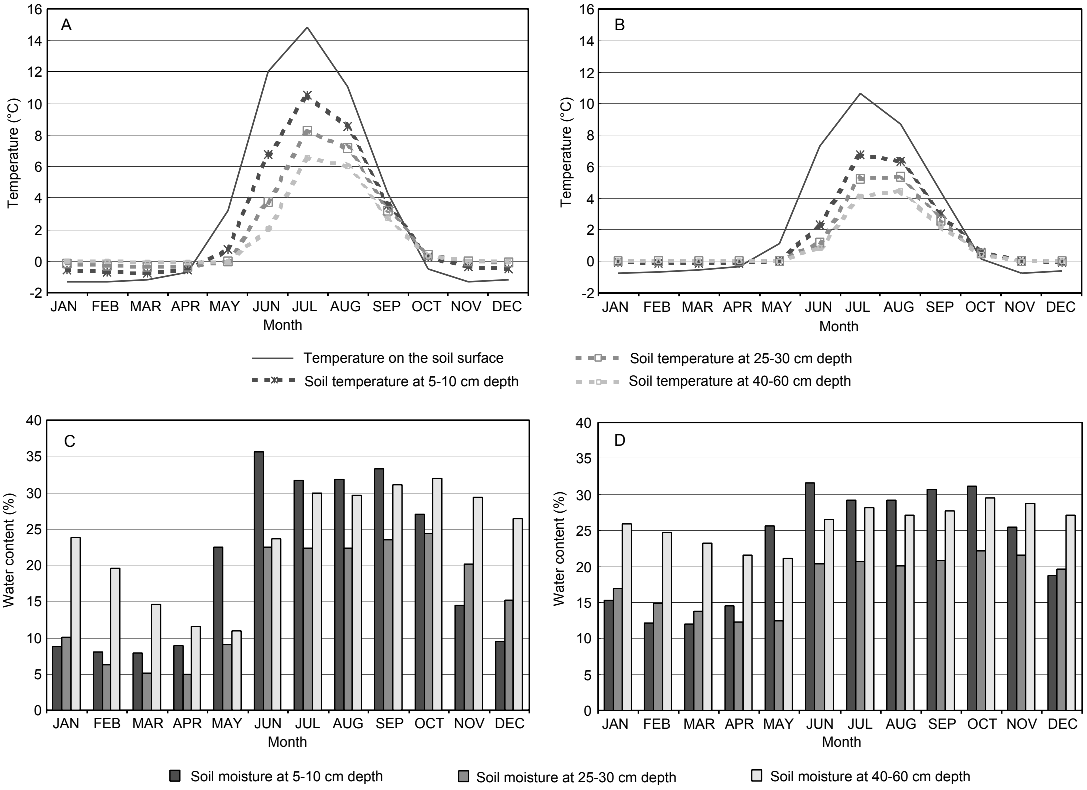

Fig. 9. Annual cycles of the surface temperature, soil temperature and soil moisture at depths of 5–60 cm derived from the simulated dataset for 1975–2003 for (**A**, **C**) treeless vegetation and (**B**, **D**) forest.

soil surface was 4.8 °C larger at the open site than in the forest, and 3.5–5 °C larger for the soil temperature in the three layers analysed. In the seasonal variation the differences were less pronounced during winter (less than 1 °C) and more significant during summer (4–5 °C). The simulated mean maximum thickness of the snow cover was 20 cm greater in the forest (110 cm) than over the tundra vegetation, where the mean maximum over the simulated period was 91 cm. The snowmelt was delayed by about 6–12 days in the forest as compared with that at the open site. The mean annual soil water content was quite similar at the two sites. The seasonal variations of the soil moisture in different layers are marked by higher values during the warm season at the open site and the other way round during the winter; however, the winter-time differences between the two sites are smaller (Fig. 9).

The accumulated evaporation in 1975–2003 was about 48% more over the forest than over the tundra vegetation. Similar to the one-year simulations, the soil evaporation was the main component in the evaporation from the site covered by low vegetation, while the transpiration and interception evaporation were the determining evaporation forms over the forest. The transpiration varied between 6.3–50 mm month^{-1} from May until the end of September for the forest and 1.3–20 mm month^{-1} for the tundra vegetation (Fig. 10), while the evaporation from the soil surface ranged between 13–32.7 mm month^{-1} for the tundra vegetation and 3–7.7 mm month^{-1} for the forest.

The latent heat flux had higher values over the forest throughout the year, accounting for about 53 W m^{-2} higher latent heat flows. Similarly, the sensible heat flux from the forest exceeded that from the low vegetation in every season; however, after the maximum in heat flow in May from the forest and in June from open site, the discrepancy is smaller until October.

Since we could not simulate the heat and water fluxes during the period actually follow-

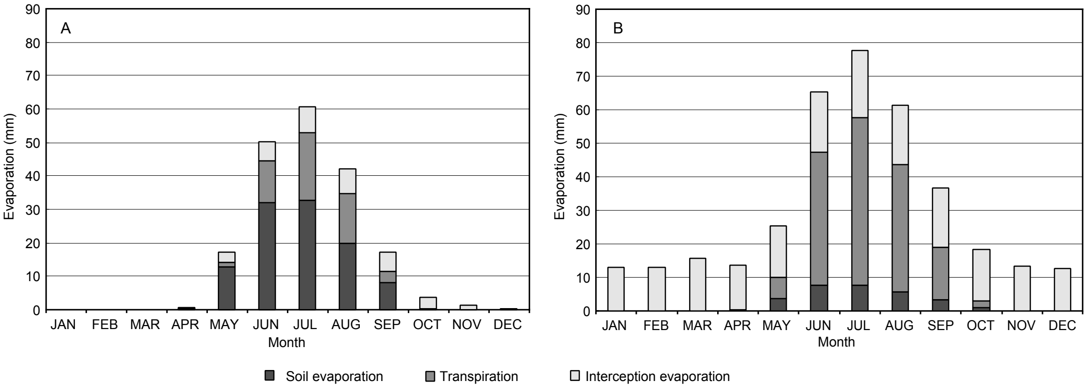

Fig. 10. The seasonal variation of evaporation and its components derived from the simulated dataset for 1975–2003 (**A**) at the treeless site and (**B**) in the forest.

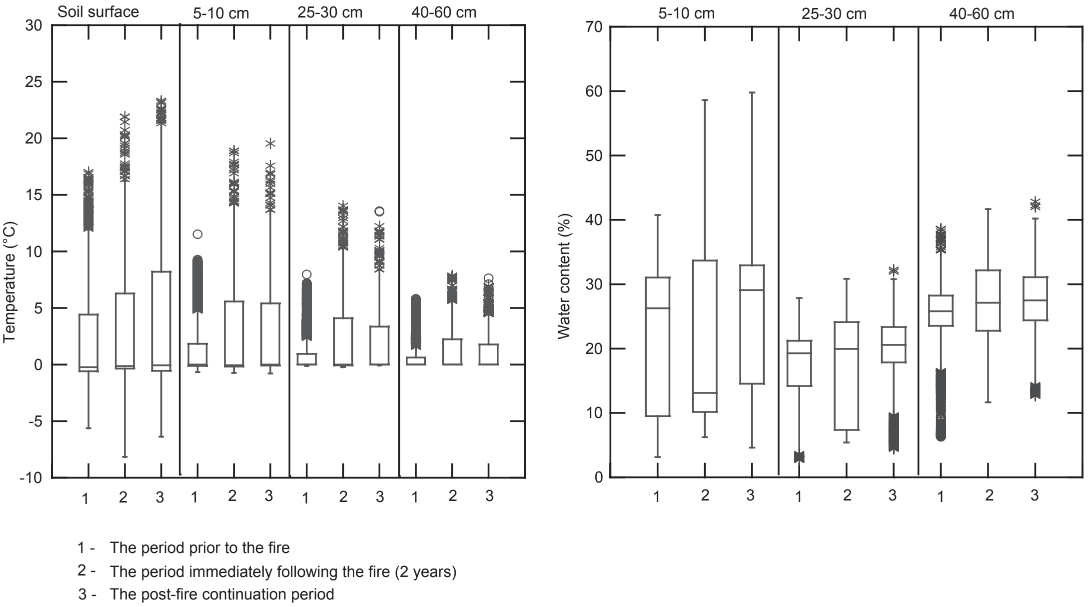

Fig. 11. The soil temperature and water content at depths of 5–60 cm for the simulated pre-fire, immediate post-fire and post-fire continuation conditions. The horizontal line within the box corresponds to the median and the end of the box to the interquartile range; the "whiskers" give extreme values within –1.5 and 1.5 times the interquartile range. Values outside –1.5 and 1.5 times the interquartile range are shown with circles.

ing the fire from 1960 onwards, we tried to set up the pre-fire conditions at the study site and the post-fire conditions created by a potential fire during the 28-year modelling period (1975–2003). The variations of soil temperature, water content and evaporation were analysed in this experiment (Fig. 11). The mean soil surface temperature during the three distinct periods differed by 1.8 °C, while the soil temperatures deviated by 0.4–1.4 °C, with lower values at greater depths. Nevertheless, the variation of temperatures exhibited a large range of values in the cases of a burned area and that with low vegetation, confirming the lower thermal conductivity of the tundra-covered soil surface. The mean daily water contents of the soil layers were higher during the post-fire conditions. Furthermore, the variation in the values indicates both a rapid accumulation of moisture and a vigorous desiccation of the subsoil in the case of poor

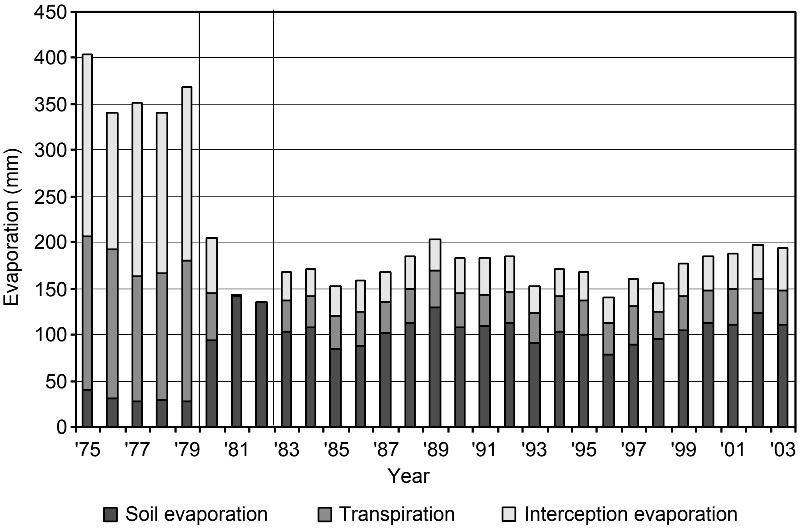

Fig. 12. The mean annual evaporation and its components for the simulated pre-fire, immediate post-fire and post-fire continuation conditions.

vegetation. Similar patterns in the soil moisture variation appeared in the deeper soil layers.

Annual evaporation was highest in forest during the pre-fire conditions and lowest in the years immediately following the fire (Fig. 12), when the evaporation was composed mainly of soil evaporation. The variations in transpiration and interception evaporation show similar patterns to those delineated in the previous subchapter.

Discussion

This study investigates the distinction between the local climate of a fire-impacted area and a forest. The variations in air temperature and relative humidity were similar at the two sites. The mean air temperature variation was only 0.2 °C between the forest and tundra vegetation and the extremes of air temperature were similar, as well. This variation partially differs from those reported elsewhere concerning clear-cut areas and forest sites (Chen *et al.* 1993, Carlson and Groot 1997). Although the clear-cut site was found to be warmer, the magnitude of the changes was higher (0.6–0.7 °C) in the studies mentioned.

The variation in soil temperature was relevant and shows typical differences between the two surface types. The interception of the solar radiation by vegetation strongly influences the soil heat flux and the soil temperature (Oliver *et al.* 1987). Removal of the original vegetation and its substitution by low vegetation increased the direct insolation to the soil surface, resulting in higher temperatures during summer. The canopy and the abundant ground vegetation in the spruce forest absorbed a larger fraction of radiation and substantially reduced the irradiance of the soil surface. Due to this protecting feature of the vegetation and to the thicker snow cover, the variation of soil temperature is moderated in the forest and the depth and length of the soil frost is reduced. The soil frost occurring down to a depth of at least 0.5 m in the open area could be crucial for the survival of plants. Although on an annual average, the soil in the forest at all the measured depths was warmer than that of the open site, the oscillation between the extremes and the cumulative soil temperature during the growing season was the major difference at the open site. Similar differences in the soil temperature of different surfaces were reported from Canada (Carlson and Groot 1997) and UK (Proe *et al.* 2001). The sites considered in both studies had been recently impacted by timber harvesting, thus the differences between the clear-cut area and the forest during the summer were slightly higher (2 °C) than in the present study (1.2 °C).

The removal of tall vegetation from the affected site resulted in a large increase in wind velocity. The altered surface roughness induced a 60%–65% stronger wind over the open site compared with the spruce forest and an increased probability of high wind speeds (A. Vajda *et al.* unpubl. data). The increased wind speed can have both mechanical and physical effects upon plants. Wind speed probably influences plants by causing changes in the vapour pressure deficit that may affect stomatal conductance. Although plants can respond to increased wind in the short-term through stomatal closure, prolonged exposure to high winds can lead to abrasion of the cuticular waxes (Van Gardingen and Grace 1991). Furthermore, wind is an essential factor in snow accumulation, which in turn may directly or indirectly affect plant development. The high wind flow velocity over the low vegetation area gives rise to more vigorous snow drifting and thereby to a 20–30 cm thinner snow cover. Deep, insulative snow assures greater protection from winter desiccation, wind abrasion (Sturm *et al.* 2001) and frost activity. The amount of snow accumulated during the winter season determines the soil moisture during spring and early summer.

In general, the soil in the spruce forest had higher moisture levels than that at the open site, except for the topsoil, where the higher sand content of the forest soil permitted a faster permeation of water. Due to the reduced vegetation, the soil at the open site was more receptive to variations in precipitation during the warm season and variations in temperature in wintertime. The canopy and the dense ground vegetation in the forest catch a fraction of the precipitation, hereby precluding both excessive moisture supplementation and the desiccation of the soil. The evaporation and the rates of its components during the observation period differed significantly over the study area. The amount of evaporated water was persistently higher over the spruce forest. The annual totals of the evaporation components confirm the dominance of transpiration, except during the spring and autumn, whereas the rate of interception evaporation and soil evaporation were substantial. Contrary to the forest, the dominant evaporation component over the open site was the soil evaporation. This is explained by differences in the development of the leaf area index, canopy surface resistance and the higher interception storage of the forest. As leaf area increased, shading of the ground may strongly impede soil evaporation but at the same time transpiration may increase (J. Beringer *et al.* unpubl. data). Additionally, the differences between the observed precipitation and evaporation were somewhat less over the tundra, making it drier than the spruce forest.

The effect of surface properties on the energy fluxes stands out from the simulations. The amount of energy used in latent heating consists of the evaporation and transpiration components. As the evaporation, the latent heat flux too was higher in the spruce forest. During May–August, the important season for plant development, latent heating showed 8–14 W m^{-2} higher values in the forest, taken over the period 1975–2004. However, the wintertime values resulting from condensation were unexpectedly large over the forest; the reason for this is uncertain. Sensible heat fluxes are of primary interest, as they have a direct effect on the local and regional climate through heating of the boundary layer (Oke 1987). According to both the short- and long-term simulations, the summer-time sensible heating increases as the vegetation becomes denser. The difference between the sites was 10 W m^{-2} for the simulation period. Considering just the summer of 2004 (May–August), the average Bowen ratio for the forest was 0.9, with the value for the tundra vegetation being 0.8; the results of long-term simulations, however, indicate a lower value of 0.4 for tundra. Our Bowen ratio values are consistent with other studies, for example spruce forest Bowen ratios between 0.5–1.5 have been reported (Gustaffson *et al.* 2004, J. Beringer *et al.* unpubl. data) and for tundra values between 0.3–1 (J. Beringer *et al.* unpubl. data). The increase in the ratio of sensible heat to latent heat from tundra to forest indicates the increasing dominance of sensible heating as an energy source for the atmosphere in the case of the latter.

Similar patterns appeared in the long-term seasonal variation of climatic and soil parameters. The differences in the heat, water flow and radiation processes between the sites are persistent; in accordance with this, as the 1975–2004 measurements and simulations indicate, the climate of the Tuntsa region became slightly warmer and wetter. According to our simulations, the occurrence of a fire in a spruce forest near the tree-line results in more unfavourable climate and soil conditions for vegetation, manifested in changes in the soil temperature regime, in a considerable accumulation of water content in the topsoil, stronger winds and reduced evaporation and snow cover.

Forest regeneration requires suitable environmental conditions, such as a beneficial temperature and light quality, sufficient, but not excessive soil moisture, especially in early seedling survival, and reduced soil frost during winter. The changed post-fire environmental factors following the 1960s fire and the severe climatic conditions on the burned area may have had negative effects on seedling growth and survival. Although several cases have been reported of post-fire forest regeneration in favourable conditions in Fennoscandia (Lampainen *et al.* 2004), the recovery of boreal forest trees, e.g., Scots pine, near the climatological tree-limit has remained reduced. In contrast to the poor regeneration on the Finnish side of the burned area, it was abundant on the Russian side, probably because of the changed local climatological conditions, the high logging intensity of damaged trees after the fire in Finnish Lapland and reindeer husbandry.

Reduced post-fire tree regeneration in the boreal-subarctic ecosystem has been reported from the Canadian Arctic treeline as well (Sirois and Payette 1991, Arsenault and Payette 1992, 1997). The low regeneration of trees resulted in decreased tree-productivity in subarctic forests. The absence of post-fire regeneration changed the vegetation cover in the former boreal forest towards forest-tundra and lichen-tundra. Considering the fire frequency along the boreal forest-tundra interface and the environmental consequences of the fires, this boundary may suffer sudden fragmentation caused by climate–fire interactions (Sirois and Payette 1991).

Conclusions

The direct measurements of the local climate on a fire-impacted opening and in a spruce-covered fire refuge, and the simulated energy and water fluxes, emphasize the differences between the soil heat and moisture, evaporation and radiation processes for the two surface types. Removal of the original vegetation by fire and its substitution by tundra vegetation effected a large seasonal variation of soil temperature associated with deep soil frost, an increased wind velocity (60%–65% stronger than in the forest) and 20–30 cm reduced snow cover. The soil water content variation beneath the low vegetation was considerable, especially during the warm season, although in the long run the soil from the forested site was moister. The changes in evaporation and energy fluxes were mainly determined by the structural parameters of the canopy. The amount of evaporated water and the heat fluxes from the forest exceeded that from the tundra vegetation.

In conclusion we see that following the 1960s fire, due to the altered surface conditions, the local climate and soil conditions in the Tuntsa area became more unfavourable. Although we have not studied the progress in the recovery of any species in particular, we can say for sure that the changed environmental conditions negatively affected the recovery of vegetation in the sensitive region near the climatological tree-line.

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