FINNISH METEOROLOGICAL INSTITUTE
CONTRIBUTIONS

No. 64

SPATIAL VARIATION OF CLIMATE AND THE IMPACT OF DISTURBANCES ON LOCAL CLIMATE AND FOREST RECOVERY IN NORTHERN FINLAND

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ACADEMIC DISSERTATION
To be presented, with the permission of the Faculty of Science of the University of Helsinki, for public criticism in Auditorium XII of the University's Main Building, Unioninkatu 34, on 20th of October 2007, at 10 a.m.

Finnish Meteorological Institute
Helsinki, 2007

ISBN 978-951-697-629-0 (paperback)
ISSN 0782-6117
Yliopistopaino
Helsinki 2007

ISBN 978-952-10-4187-7 (PDF)
http://ethesis.helsinki.fi
Helsinki 2007

FINNISH METEOROLOGICAL INSTITUTE

Series title, number and report code of publication
Contribution No. 64, FMI-CONT-64

Published by Finnish Meteorological Institute
(Erik Palménin aukio 1), P.O. Box 503
FIN-00101 Helsinki, Finland

Date: September 2007

Authors

Name of project

Andrea Vajda

Title

Spatial variation of climate and the impact of disturbances on local climate and forest recovery in northern Finland

Abstract

The structure and function of northern ecosystems are strongly influenced by climate change and variability and by human-induced disturbances. The projected global change is likely to have a pronounced effect on the distribution and productivity of different species, generating large changes in the equilibrium at the tree-line. In turn, movement of the tree-line and the redistribution of species produce feedback to both the local and the regional climate. This research was initiated with the objective of examining the influence of natural conditions on the small-scale spatial variation of climate in Finnish Lapland, and to study the interaction and feedback mechanisms in the climate-disturbances-vegetation system near the climatological border of boreal forest.

The high (1 km) resolution spatial variation of climate parameters over northern Finland was determined by applying the Kriging interpolation method that takes into account the effect of external forcing variables, i.e., geographical coordinates, elevation, sea and lake coverage. Of all the natural factors shaping the climate, the geographical position, local topography and altitude proved to be the determining ones. Spatial analyses of temperature- and precipitation-derived parameters based on a 30-year dataset (1971-2000) provide a detailed description of the local climate. Maps of the mean, maximum and minimum temperatures, the frost-free period and the growing season indicate that the most favourable thermal conditions exist in the south-western part of Lapland, around large water bodies and in the Kemijoki basin, while the coldest regions are in highland and fell Lapland. The distribution of precipitation is predominantly longitudinally dependent but with the definite influence of local features.

The impact of human-induced disturbances, i.e., forest fires, on local climate and its implication for forest recovery near the northern timberline was evaluated in the Tuntsa area of eastern Lapland, damaged by a widespread forest fire in 1960 and suffering repeatedly-failed vegetation recovery since that. Direct measurements of the local climate and simulated heat and water fluxes indicated the development of a more severe climate and physical conditions on the fire-disturbed site. Removal of the original, predominantly Norway spruce and downy birch vegetation and its substitution by tundra vegetation has generated increased wind velocity and reduced snow accumulation, associated with a large variation in soil temperature and moisture and deep soil frost. The changed structural parameters of the canopy have determined changes in energy fluxes by reducing the latter over the tundra vegetation. The altered surface and soil conditions, as well as the evolved severe local climate, have negatively affected seedling growth and survival, leading to more unfavourable conditions for the reproduction of boreal vegetation and thereby causing deviations in the regional position of the timberline. However it should be noted that other factors, such as an inadequate seed source or seedbed, the poor quality of the soil and the intensive logging of damaged trees could also exacerbate the poor tree regeneration.

In spite of the failed forest recovery at Tunsta, the position and composition of the timberline and tree-line in Finnish Lapland may also benefit from present and future changes in climate. The already-observed and the projected increase in temperature, the prolonged growing season, as well as changes in the precipitation regime foster tree growth and new regeneration, resulting in an advance of the timberline and tree-line northward and upward. This shift in the distribution of vegetation might be decelerated or even halted by local topoclimatic conditions and by the expected increase in the frequency of disturbances.

Publishing unit
Finnish Meteorological Institute, Climate and Global Change Research

Classification (UDK)
551.584.2
630*43

Keywords
Lapland, Kriging, spatial variation of climate, arctic timberline, forest fire, post-fire environmental conditions, forest recovery

ISSN and series title
0782-6117 Finnish Meteorological Institute Contributions

ISBN	Language	
978-951-697-629-0	English	
Sold by	Pages	Price
Finnish Meteorological Institute / Library	139	
Erik Palménin aukio 1	Note	
00560 Helsinki, Finland		

ACKNOWLEDGEMENTS

This study was carried out at the Finnish Meteorological Institute during 2002-2006. I would like to express my deep gratitude to my supervisors Docent Ari Venäläinen (Finnish Meteorological Institute) and Professor Matti Seppälä (Department of Geography, University of Helsinki) for providing me with the opportunity to do this research and for the valuable discussions, guidance and support in completing my thesis. Thank you, Ari for initiating this project and for your help in obtaining funding for it.

I am also grateful to the pre-examiners of this thesis, Professor Leif Kullman and Docent Björn Holmgren for their constructive criticism and Professor Friedrich-Karl Holtmeier for serving as opponent at the defence of this dissertation. Thanks are also due to Mr. Robin King for his valuable linguistic guidance throughout the work.

All my co-authors are acknowledged for the valuable discussions and their contribution to the articles. I would also like to thank my colleagues at FMI’s Arctic Research Centre, Sodankylä for their helpful support in collecting regularly the measurement data from Tuntsa test site as well as the staff of the Geological Survey of Finland, Rovaniemi for their assistance in carrying out the snow measurements in Tuntsa.

I wish to express my sincere thanks to Professor Mikko Alestalo, Professor Heikki Järvinen and Dr. Juhani Damski for providing excellent working conditions at the Institute, as well as Drs. Kirsti Jylhä and Pertti Nurmi for their help and support with various research projects. I thank all my colleagues from the Climate Research and Meteorological Applications groups at FMI, for creating a friendly working atmosphere.

In the first phase of the work financial support was granted by the Maj and Tor Nessling Foundation.

Finally, I am indebted to my parents, Antal and Juliánna, for their love and support: Szívbõl köszönöm! Special thanks go to my friends who made my stay in Finland truly enjoyable through numerous trips and social happenings, attenuating my homesickness. Last but not least, I wish to express my deepest gratitude to my husband András for giving me invaluable support and encouragement throughout these years and for loving me unconditionally even in those difficult moments when it may have seemed hard to do so.

Helsinki, August 2007
C. Andrea Vajda

CONTENTS

1. INTRODUCTION

It is climate that defines to a large extent the limits for terrestrial ecosystems. The components of ecosystems, such as plants, animals, soil biota and their environment are all affected by climate variability and change, but through widely differing pathways and at different scales (IPCC 2001). The impact of climate change and variability on the biosphere varies from the global to regional and local scales. Regional and local climate changes induced by human activities include those caused by extensive changes in land use, for example due to the influence of agriculture, forestry, draining of peatlands and fire (Meng et al. 1995, Bonan 1997, Stohlgren et al. 1998, Copeland et al. 1996, Pan et al. 1999, Solantie 1994, Venäläinen et al. 1999).

Finnish Lapland, situated in the northern part of Finland, lies in the transition phytogeographic region between the forested boreal zone and the sub-arctic zone dominated by treeless tundra vegetation (Hustich 1966, Timonen and Varmola 1985, Heikkinen 2005). Consequently, it includes the tree line of some deciduous species of the genus *Betula* and *Populus* and coniferous species, such as *Pinus* and *Picea* (Hustich 1966, Seppälä and Rastas 1980), as well as the transition forest-tundra belt. At high latitudes, near the climatological limit of occurrence of many species, any changes in climate may have a large influence on vegetation, as trees and forests grow close to their ultimate ecological tolerance limits (Kullman 1998, Lee et al. 2000). The projected global climate change indicates a particularly large warming trend, affecting most significantly high latitudes of the northern hemisphere (Jones and Moberg 2003). Changes in temperature and precipitation regimes are likely to have pronounced effects on the distribution and productivity of boreal forests and arctic vegetation.

Studies of the atmosphere, soil and vegetation have indicated pronounced effects of global change in Finland (Carter et al. 2004, Jylhä et al. 2004, Tuomenvirta 2004), including an overall rise in annual temperature, especially in spring and winter, an increased length of the growing season and a reduced extent of snow cover. The climate-change scenarios project further warming and wetting trends for Finland during the 21st century, marked by an increase of 2-7 °C in annual temperature and a 5-40% in precipitation by 2080 (Jylhä et al. 2004). The changed climate conditions are likely to alter the dynamics of the cold-environment ecosystems. A warmer climate and changes in the precipitation regimes trigger (1) shifts in the distribution and productivity of vegetation, (2) an expansion of boreal forest into tundra regions, (3) alteration of community composition and (4) an increase or decrease in the growth of various species (Bonan et al. 1992, Chapin et al. 1995, Lloyd and Fastie 2002, Kullman 2005b). For example, the yield of Scots pine and downy birch has been predicted to increase in northern Finland, while the productivity of Norway spruce is expected to decrease in the south but to increase in the north (Kellomäki and Kolström 1994, IPCC 1997). Several studies suggested a decline in tree growth at the tree-line in Eurasia (Vaganov et al. 1999) as well as in Canada (Lloyd and Fastie 2002). On the other hand, the interaction of climate variation with human-induced changes generates large changes in the equilibrium at the tree-line. Increased land-use, changes in grazing, the fire regime, timber harvest and insect outbreaks can lead to a long-term irreversible feedback in which the forest does not recover and the tree-line retreats southwards even in a warming climate (Chapin et al. 2004).

Change is also expected in the disturbance regimes in northern regions. Fire is one of the dominant forms of disturbances in the boreal forest and in the transition zone between forest and tundra (Kasischke and Stocks 2000); the increased climatic stress and the climatically-driven changes in vegetation will probably result in an increase in fire risk, burnt area and fire frequency (Starfield and Chapin 1996, Flannigan et al. 2005).

A future redistribution of vegetation in the high-latitude ecosystems could initiate important positive and negative climate feedbacks, which would affect the climate on local, regional and even global scales. The expansion of the boreal forest into the tundra region could significantly affect the surface albedo, foster the rate of regional warming (Bonan et al. 1992, Bourque et al. 1995, Chapin et al. 2000, Rupp et al. 2002) as well as alter the ecosystem's CO_2 fluxes. Alternatively, the disturbed near-surface environment may have a negative feedback on local climate, leading to climatic conditions that become more unfavourable, including more extreme surface and soil temperatures, lower humidity, increased wind speed and altered evaporation (Carlson and Groot 1997); there may also be a reduced snow cover, which enhances frost disturbances (Arsenault and Payette 1997) and induces water stress that in turn lowers tree productivity (Sirois and Payette 1991). The changed climate and soil patterns can have a strong influence on forest regeneration at the northern climatological tree-line.

Although fires have many vital functions in the boreal ecosystem, enhancing spatial heterogeneity, maintaining a mosaic of patches in the landscape and, under favourable climatic conditions, inducing abundant regeneration (Landhausser and Wein 1993, Lampainen et al. 2004), many studies have reported post-fire degradation or the disappearance of conifer stands at the tree-line, resulting in changes from a boreal to an arctic landscape (Sirois and Payette 1991, Arsenault and Payette 1992, 1997, Arseneault 2001). The interactions between climate, vegetation and disturbances, e.g., forest fires, are complex and still poorly understood.

1.1 Aims of the study

The main purpose of the present study is to enhance knowledge about the interaction and feedback processes between climate-surface-vegetation in the sensitive subarctic ecosystem near the northern timberline. To achieve this goal the following specific objectives were targeted:

- To determine the influence of geographical factors, such as geographical location, elevation, lakes and sea on the spatial variation of regional climate in northern Finland (Lapland)
- To assess the small-scale spatial variation of several climatological parameters in Lapland by applying and testing a high resolution (1 by 1 km) spatialization method

- To examine the influence of vegetation on the small-scale spatial variation of snow depth at a fire-disturbed timberline and the implications of altered snow conditions for the preconditions of forest regeneration
- To examine how the human activities, such as forest fires, impact the climate on a local scale and to study the effect of the changed environmental conditions on the vegetation regeneration at the climatological borderline of boreal forests.

1.2 List of original publications

This thesis is based on the following research articles, referred to in the text by their Roman numerals:

I Vajda, A. and Venäläinen, A., 2003: **The influence of natural conditions on the spatial variation of climate in Lapland, northern Finland**. *International Journal of Climatology*, **23 (9)**, 1011-1022.

II Vajda, A. and Venäläinen, A., 2003: **Small-scale spatial variation of climate in Finnish Lapland**. *Finnish Meteorological Institute Reports,* Helsinki, **2003/1**, 34 p.

III Vajda, A., Venäläinen, A., Hänninen, P. and Sutinen, R., 2006: **Effect of vegetation on snow cover at the northern timberline: a case study in Finnish Lapland**. *Silva Fennica* **40 (2)**, 195-207.

IV Vajda, A. and Venäläinen, A., 2005: **Feedback processes between climate, surface and vegetation at the northern climatological tree-line (Finnish Lapland)**. *Boreal Environmental Research* **10**, 299-314.

Papers I-IV are reprinted at the end of this thesis. The papers are reproduced by kind permission of the journals concerned.

The author of this thesis bore the main responsibility for writing all four articles included in the thesis. The development of a high-resolution Kriging interpolation method and its applicability in Finland, presented in **Paper I** and **II,** were carried out by the author together with Dr. A. Venäläinen. The author performed all of the analysis and calculations in **Papers II**, **III** and **IV** as well as preparing the climatological maps for **Paper II**. The model simulations in **Paper IV** were provided by the author, while those in **Paper III** were performed together with Dr. A. Venäläinen. The author participated in the snow measurements during the field campaign in winter 2002-2003 (**Paper III**), in the installation of the weather station and in the measurements. The radar measurements of snow depth were carried out by Dr. R. Sutinen and Dr. P. Hänninen. In all the papers Dr. A. Venäläinen acted as supervisor and provided valuable comments on the content and format of the papers.

2. THE SYSTEM STUDIED

2.1 Regional and local climate

Regional climate is defined by geographical and homogeneous climate features or by political and physiographic boundaries (IPCC 2001). In this respect the lower limit of the regional scale is 10^4 km^2, while the upper limit is generally 10^7 km^2, although the latter is often referred to as the sub-continental scale. Regional climate is determined by the interaction of regional and local-scale forces and circulations that occur at planetary, regional and local scales. Regional climate forcing includes factors such as geographical location, complex topography and elevation, distribution of land and water masses, land-use characteristics, atmospheric concentration of aerosols and regional circumstances such as ocean currents, prevailing wind direction and snow and ice distribution.

Local climate is defined by the *Encyclopedia of World Climatology* as the climate in an area where the local conditions of the Earth's surface are clearly different from those in nearby surrounding areas, for example regarding hills, forest, city, croplands, rivers and a mountain environment (Oliver 2005). It comprises a number of microclimates within an area of distinctive surface features (Schneider 1996). With reference to the size of a local climate, different estimates have been used by different researchers, but in general its extent may vary horizontally from 10^2 m to 10^4 m and on the vertical scale from 1 cm up to 1 km. Contrary to global climate, local climate is not affected by latitude but by topography, land and sea distribution and ground cover (Oliver 2005). Thus the physical processes affecting the local climate are determined by the location and exposure of the area and by surface conditions, such as heat capacity, moisture content, vegetation cover, albedo and roughness of the ground surface.

2.2 The influence of natural conditions on the spatial variation of climate in Lapland

The primary geographical influences in forming the climate of a region are latitude, the Earth's surface topography and the proximity to large bodies of water (Schneider 1996). The latitudinal location of a region determines the angle at which the sun's rays strike the earth, the length of the day and the amount of solar radiation received, and thus determines its temperature. In addition, the distribution of land and water bodies as well as the altitude of the site or topographic barriers may induce changes in the spatial and temporal variation of temperature, pressure, precipitation and wind regime. The principal factor responsible for shaping the climate of Fennoscandia and thus of Lapland is the northern location of the region and the influence of the North Atlantic Drift, which together with the westerly and south-westerly winds serves to transfer heat from south to north (Tikkanen 2005). The proximity of the Atlantic in association with the effect of the Baltic Sea and Arctic Ocean makes the climate of Lapland intermediate between maritime and continental, having climatic features in common with the Arctic (Laaksonen 1977, Seppälä and Rastas 1980, Tikkanen 2005).

On a topographical basis, Lapland constitutes part of an upland region, characterized by plains at 200-500 m a.s.l. with residual, gently-sloping hills typical of old peneplain surfaces. The highest elevations are found in the mountainous region in the W and NW (the eastern flank of the Scandinavian mountains), with heights ranging between 500-800 m a.s.l. and individual peaks reaching above 1000 m a.s.l. A major low-lying area extends around Lake Inari in the north, with the lake surface at 119 m a.s.l. (Lidmar-Bergström and Näslund 2005). Deep fault valleys cut through the blocks in the northern part of Lapland, such as those of Teno, Utsjoki, Kevojoki and Vaskojoki; these valleys are very different in their topography and environmental conditions (Seppälä and Rastas, 1980). Thus the regional distribution of elevation in Lapland is quite distinct, ranging from 100 m to 1300 m, resulting in local differences in the distribution of climatic elements.

Larger bodies of inland water, such as lakes, are a very important element of weather and climate, causing significant effects on climate at scales ranging from the microscale to the synoptic scale (Laaksonen 1976b, Krinner 2003, Oliver 2005). Their effects on the atmosphere vary with the areal extent, depth and configuration of the lake. Due to the thermal lag of lakes and their heat capacity, the regional climate of the surroundings is substantially modified, i.e., extremes of high and low temperatures are reduced, summer temperatures are reduced while winter temperatures are higher and the freeze-free and growing seasons are longer. Local weather is also affected by the evaporation from lakes, the changed wind patterns over the lakes and possibly by developed lake-breeze systems. Many studies have demonstrated the influence of lakes on climate parameters in Finland, including the statistically-significant warming effect of lakes on summer minimum temperatures (Solantie 1975, 1976) but less investigations have been made on the maximum temperature, the extension of the growing season or the increase in the effective temperature sum (Laaksonen 1976a). Lakes are less abundant in Finnish Lapland than in the southern and central parts of Finland; there are only three large water bodies situated in the area studied: Lake Inari (1050 km^2) situated in the north and the Lokka (420 km^2) and Porttipahta reservoirs (214 km^2) on the upper reaches of the Kemijoki system. The rest of the lakes situated in Lapland are mostly small or medium-sized.

2.3 The northern timberline and the boreal forest disturbances in Finnish Lapland

Finland is covered almost entirely by boreal vegetation, characterised by coniferous forest (Heikkinen et al. 2002). The boreal forest is bordered in the far north by treeless arctic vegetation, known as tundra. The transition from the forested boreal zone to tundra vegetation is the timberline, although it is usually more a boundary region than a distinct line (Hustich 1966, Heikkinen 2005). The term northern timberline or arctic timberline is used when referring to the latitudinal boundary between the forest and tundra in the north.

The concept and use of the terms forest-line, forest-limit, timberline and tree-line is rather inconsistent and vague. The terminology differs from one country to another, the boundary of the boreal forest being referred to as both the tree-line and the timberline. In the present study (**Papers III** and **IV**) we have applied the terminology suggested by Hustich (1966) and referred to in numerous papers (Pohtila 1997, Heikkinen et al. 2002, Holtmeier et al. 2003, Autio 2006, Juntunen and Neuvonen 2006); the timberline ecotone is the limit of the continuous or nearly-continuous forest cover and comprises different forest and tree lines, ranging from continuous forest with a good capacity for regrowth to treeless terrain. The tree-line frames the limit of the arborescent growth form, usually at least 2 m high (Hustich 1979). The use of the term 'climatological tree-line' also occurs in **Paper IV**. The timberline roughly coincides with the isotherm of 10°C for the average temperature of the warmest month. At the same time other climatic parameters, such as the length of the frost-free period, growing season, the effective temperature sum, the amount of evapotranspiration and precipitation, as well as non-climatic parameters, such as the amount of nutrient and carbon dioxide deficiency are determining factors for the position of timberline (Hustich 1966, Heikkinen et al. 2002). The main tree species in Finnish Lapland (north of 66°) are Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and downy birch (*Betula pubescens*) (Timonen and Varmola 1985, Pohtila 1997, Tasanen et al. 1998, Sutinen et al. 2002, Heikkinen 2005); of these, Scots pine is the main tree species in Lapland (Fig. 1).

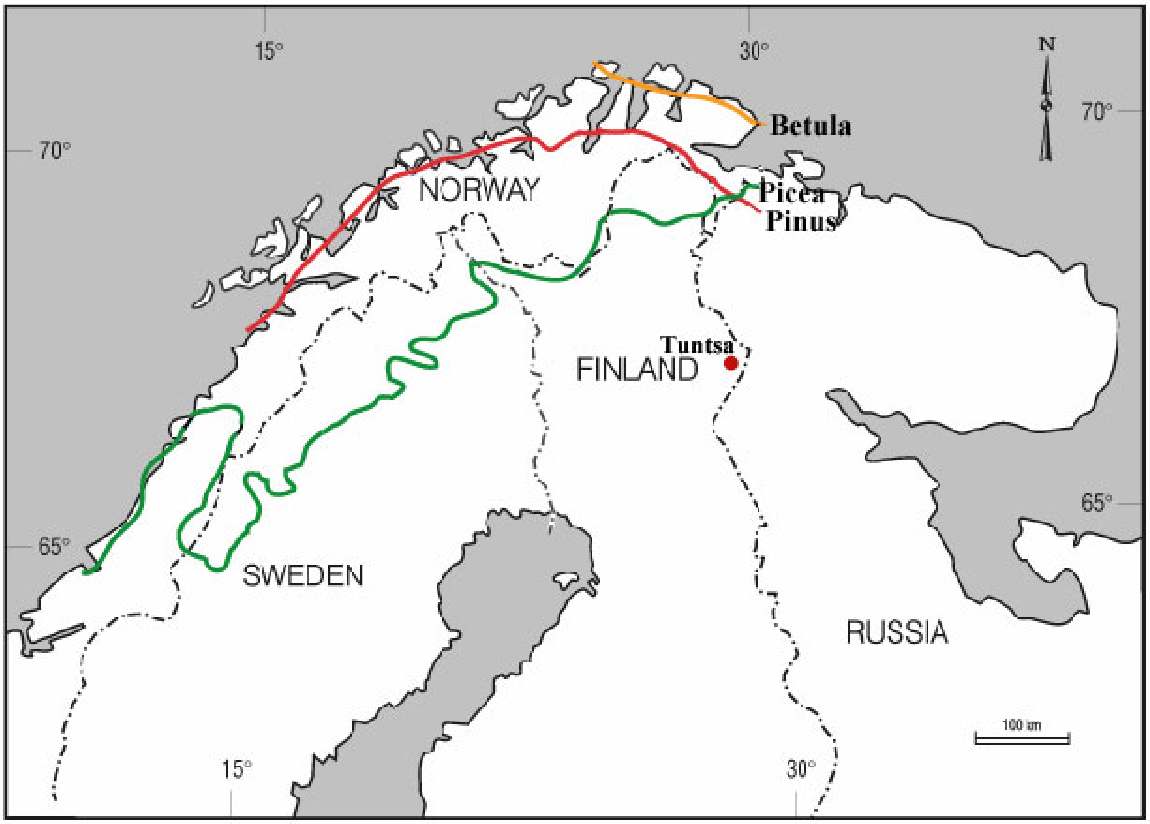

FIGURE 1. The position of the northern limits of Scots pine, Norway spruce and Betula pubescens (according to Heikkinen 2005)

The timberline is influenced by many abiotic (climate, soil, topography), biological (plant diseases, animals and insects outbreaks) and anthropogenic factors (forest fires, grazing, harvesting, industrial activities) (Oksanen et al. 1995, Herder den 2003, Svenbjörnsson et al. 2002, Autio 2006). In fact, the pattern of the dominant tree species in the boreal forest landscape, as well as the position of timberline, is a product of interaction between climate, soil conditions and the disturbance regime (Bradshaw 1993). A disturbed area can easily turn into tundra-like vegetation, and the timberline shifts southwards and to lower altitudes (Heikkinen et al. 2002). For example, the Tuntsa district of Salla (67-68° N) in central Finnish Lapland, located 200-250 km south of the arctic timberline but close to the altitudinal timberline, underwent substantial changes in its local climate and environmental conditions as a consequence of a widespread forest fire. The changed local conditions impeded the recovery of the original tree vegetation, replacing it by tundra-like short vegetation and creating a potential shifting of the timberline.

Disturbances are crucial factors in vegetation dynamics, in the creation and maintenance of physical and biological diversity (Picket and White 1985, Engelmark et al. 1993). Human activities have a substantial impact on the boreal forest and timberline through clear-cut harvesting for construction, fires, reindeer husbandry, industrial activities and the establishment of recreational areas. Of all the above-mentioned human activities, the effect of forest fires and grazing are likely to be the most essential disturbances in Finnish Lapland. Forest fires are the most significant disturbance pattern in the boreal forest (Zackrisson 1977, Kasischke and Stocks 2000), creating a mosaic of burnt and unburnt patches, maintaining vegetation diversity and stability at the landscape level (Kauhanen 2002) and triggering tree regeneration. On the other hand, fires may destroy the soil, leaving barrens that take a long time to regenerate. If the forest fire takes place on sandy soil, destroying or damaging the vegetation cover, deflation processes can be activated for long periods and the regeneration of the forest may be delayed (Seppälä 2004). The number of forest fire incidents in Lapland is lower than that in southern regions of Finland, albeit those occurring can burn out large areas. Most of the fires are caused by humans, only 13% of the total number of fires being lightning-ignited (Larjavaara 2005). However, under favourable climatic conditions, post-fire recruitment may induce an abundant regeneration (Landhausser and Wein 1993, Lampainen et al. 2004). The ecological role of fires may differ significantly towards the northern limit of the forest (Hustich 1966), where, due to the extreme climate conditions, post-fire regeneration may encounter set-backs, resulting in a major loss in tree population (Juntunen and Neuvonen 2006).

Furthermore, herbivores can affect tree growth and reproduction at the timberline and treeline (Oksanen et al. 1995, Holtmeier et al. 2003, Cairns and Moen 2004). Reindeer stocks have greatly increased since the 1970s, registering over 204 000 head of reindeer in Lapland by 2005 (source: Metsähallitus 2006). The grazing of such large numbers of reindeer has directly affected the sensitive northern ecosystem by hampering the establishment and early growth of tree seedling and the health of dwarf shrubs and lichen. Grazing also significantly reduces shoot length, accelerating the dieback of shoots, and has an indirect impact by changing the soil ecological conditions (Herder den 2003, Holtmeier et al. 2003, Cairns and Moen 2004).

3. METHODS AND MATERIAL

3.1 Spatialization of climatological variables using the Kriging interpolation method

Data for meteorological and climatological variables are collected from meteorological stations; they are thus only representative of the meteorological conditions at the station site and in its surroundings. Since spatially-distributed estimates of meteorological data are increasingly required as inputs to spatially-explicit landscape, regional and global models (Collins and Bolstad 1996), the spatial interpolation of point meteorological data over geographical areas or grid cells is of primary importance. Spatial interpolation may become problematic when data sets are sparse and observations widely separated. This is the case for the northern region of Finland, where the weather stations, especially those with a longer measurement period, may be separated by considerable distances.

In **Papers I** and **II**, a stochastic interpolation technique known as Kriging was applied to estimate the spatial distribution of climate parameters over Finnish Lapland. Kriging, originally developed by Matheron (1963), gives the best linear unbiased predictions of unobserved values, and provides an estimate of the variance of the prediction error (Henttonen 1991, Nalder and Wein 1998). This approach uses a semivariogram, a measure of spatial correlation between two points describing the change of the variance with distance (Collins and Bolstad 1996, Hartkamp et al. 1999, Hunter and Meentemeyer 2005). The Kriging method applied in this study was especially developed for climatological applications by Henttonen (1991), based on the rigorous description by Ripley (1981).
In the Kriging method, the value of the analyzed parameter (Z) at any location (X) is calculated as the sum of two terms:

$$Z(X) = m(X) + e(X) \tag{1}$$

where m(X) (often called the "trend" or "drift") describes the broad-scale features of the interpolation variable and e(x) is the random spatial variation (or "fluctuation") specific to the given position X.

The advantage of the Kriging method is that it can take into account external forcing variables in interpolations; such parameters as geographical coordinates (x,y), altitude of the terrain (h) and percentage share of lakes (l) and sea (s) in each grid square are included. The inclusion of external variables, especially in the case of a heterogenic landscape, is crucial, since these determine the spatial richness of the climate at the local scale (Hevesi et al. 1992, Vicente–Serrano et al. 2003). The use, for each grid cell, of topographic and geographic factors that determine the spatial distribution of the climatic variables permits the mapping of more local features.

The functional form of the trend in the program used is:

$$m(x, y, h, l, s) = a_0 + a_1x + a_2y + a_3x^2 + a_4y^2 + a_5xy + a_6h + a_7s + a_8l \qquad (2)$$

The coefficients $a_0 \ldots a_8$ were obtained using the least-squares fit method of the observed values. Because the territory studied does not include sea coverage, this variable has not been used in the interpolation.

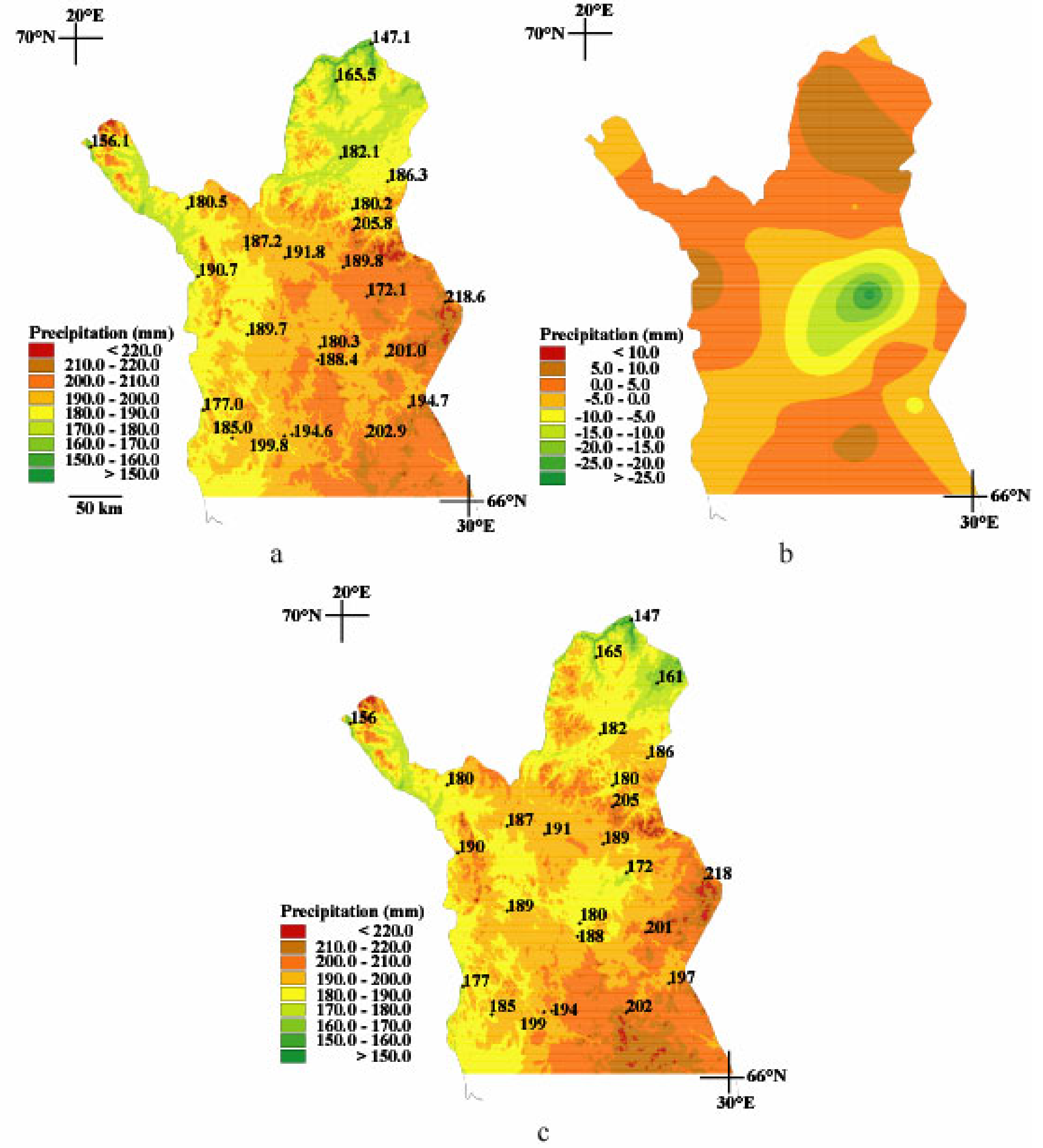

FIGURE 2. (a) The trend, (b) the fluctuation and (c) the final analysis of the spatial variation of summer precipitation (mm) in Lapland

In general, the trend function (m) defines most of the features of spatial variation and the fluctuation (e) represents the small-scale "unexpected" variation. The combination of the trend and fluctuation assures an accurate representation of the spatial variation of the parameters (Fig. 2).

Since by the use of a relatively coarse resolution of interpolation many local effects are masked, we applied the spatial modelling of climatic variables on a high spatial resolution using 1 by 1 km grid-boxes. The elevations as well as the proportion of lakes within the 1 by 1 km grids were incorporated into the model. The lake area of grid boxes was defined using the surface classification and land cover data from the 1 km Global Land Cover classification data set developed by the University of Maryland (Hansen et al. 2000). Elevation data was obtained from the Global Land One-km Base Elevation (GLOBE) project database developed by the NOAA National Data Centers (Hastings and Dunbar 1998). To estimate the effect of lakes in the waterless grid squares, the so-called "effective" lake area has been calculated for each grid based on the lake coverage of neighbouring 10 by 10 km cells (**Paper I**). This calculation brought up the problem of the exaggerated influence of smaller lakes when running the interpolation. To solve this problem, we considered the surrounding 5*5 grid-squares, with the grid-square under consideration in the middle of this quadrate. The corrected parameter was obtained as an average of the lake-coverage values of adjacent squares. In this way, the exaggerated influence of small lakes was ameliorated but the influence of larger lakes was retained.

3.2 Evaluation of the influence of 'external forcing'

To estimate the influence of external forcing on climate parameters we have selected the temperature and precipitation datasets for the period 1971-2000 from 25 stations covering the entire territory of Finnish Lapland (Fig. 3). The daily mean temperature, the maximum temperature measured at 18 UTC and the minimum temperature measured at 06 UTC were used to determine the following quantities: the lengths of the frost-free period and of the growing season, the start and the end of these seasons, degree-day values, seasonal mean of minimum and maximum temperature, extreme minimum and maximum temperature of the studied period and the daily range of temperature (annually and for summer). The computed climate parameters were interpolated on to 1 km^2 grids by running the Kriging interpolation method.

The influence of local natural variables, e.g., geographical position, elevation, lakes and sea on climatological conditions has been tested by applying a linear regression analysis that included the altitude, latitude, longitude and lake variables and by performing a comparison between the measured and modelled temperature values:

$$T= a + b_1X_1+b_2X_2+b_3X_3+b_4X_4+b_5X_5 \qquad (1)$$

where T is the air temperature in °C, X_1 is the altitude of the station, X_2 the lake variable, X_3 the latitude variable, X_4 the longitude variable, X_5 the distance from the sea, “a” is a constant and b_1 to b_5 are coefficients. The regression equation was verified by testing it against independent data.

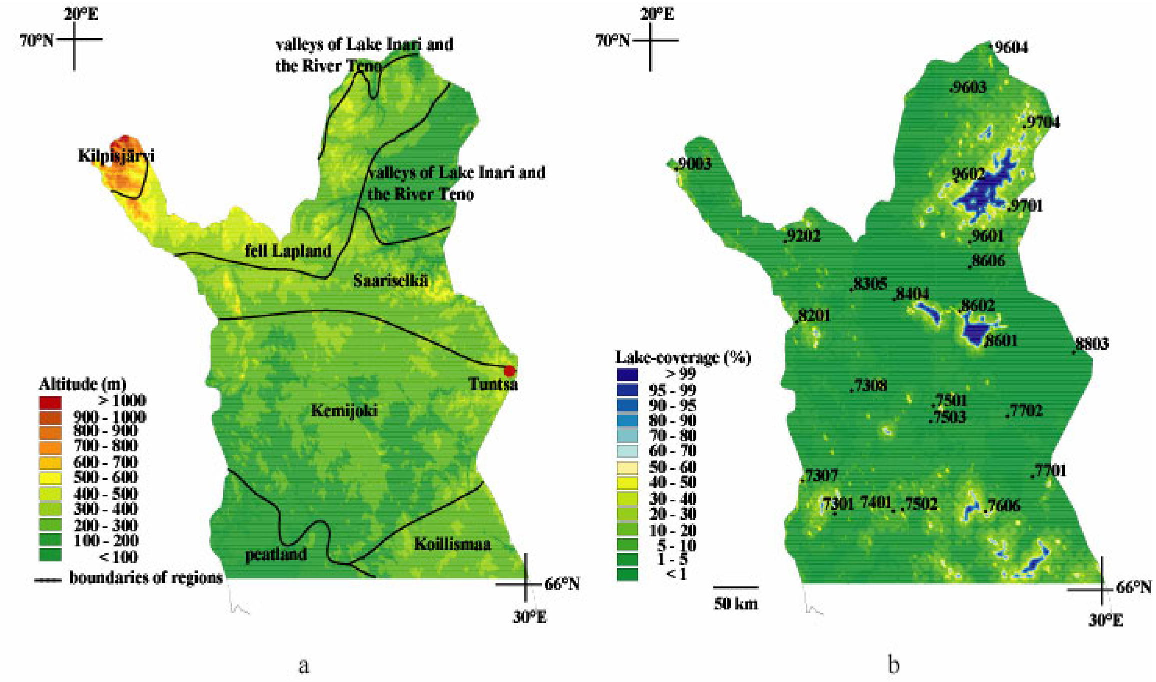

FIGURE 3. (a) The elevation of Lapland with the divisions (Solantie 1990) used in the study; (b) the lake-coverage (%) and the location of the meteorological stations used

For further analysis, the measured temperature (mean, maximum, minimum), frost-free and growing season parameters were compared with the interpolated values obtained for the corresponding grid boxes. The interpolated values were computed by including different numbers of physical parameters in the trend function.

Although, compared to the other regions of Finland, the proportion of lakes is less in Lapland, the effect of lakes on local climate may be considerable. To examine the effects of lakes, the annual cycle of temperature at stations with differing lake coverage was analyzed (**Paper I**).

3.3 Spatial analysis of climate variables

Climate variables, such as diverse indices derived from the measured parameters, provide the basis for a discussion about the regional climate and the variation of climate (Tveito et al. 2001). Based on the temperature and precipitation datasets used in **Paper I,** the spatial distribution and variation in Lapland of several climatological parameters has been studied. Maps were made of annual and seasonal mean temperature, seasonal mean of minimum and maximum temperature, mean seasonal daily temperature range, length of the frost-free period and of the growing season, the start and the end of these seasons and degree-day values. From the daily precipitation datasets, the seasonal and annual totals and annual number of days with precipitation exceeding a specific amount (≥0.1 mm) were calculated and represented in map form. The applied temperature- and precipitation-based indices were derived according to the standard methodology (**Paper II**). The spatial analysis of the climatological parameters was carried out using the Kriging spatial interpolation method with a high (1 km) spatial resolution (**Paper II**).

3.4 The human influence on local climate

3.4.1 The Tuntsa area, a fire-disturbed site in Finnish Lapland

In northern Finland, damage in forests is primarily of climatic origin. The main causes of forest damage are snow and strong winds, observed on 3.5% of forest land (Mikkelä et al. 2000) while the next most significant disturbance form is forest fire. Fire is connected with a combination of factors related to climate, vegetation and origins (Kasischke and Stocks 2000). Forest fires have been relatively small in extent, especially in recent decades due to efficient fire control, the humid climate and the relatively small amounts of dead wood in forests (Mikkelä et al. 2000). The most recent extensive forest fire in Lapland occurred in 1960 in the Tuntsa district of Salla, eastern Lapland, when ca. 20 000 ha of forest was lost. In Russian territory the affected area was even greater. The impact of human activities, such as forest fire, harvesting and grazing on local climate and thereby on the surface and vegetation near the northern timberline in the Tuntsa area has been studied (**Papers III** and **IV**).

Located between latitudes 67° and 68° N, the Tuntsa wilderness (Fig. 4-a) is situated in hilly glaciated terrain at an elevation of 300-475 m (a.s.l.). In July 1960, of the 19882 ha of vegetation that was destroyed in the Tuntsa forest fire, 9 307 ha was virgin forest, 5 051 ha krummholz and 5 524 ha was a treeless area (Haataja 1993). Prior to the fire, the area was covered by a mature (>150 yrs) Norway spruce (*Picea abies L Karst*) forest intermixed with downy birch (*Betula pubescent Ehrh.*), but with Scots pine (*Pinus silvestris L.*) 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 by seeding with Scots pine and later, up to 1976, by planting and mechanical site preparation. Despite a good start, the regeneration with pines failed on sites formerly covered by spruce. Large areas are still now treeless, having tundra-like vegetation, formed mainly by lichens, mosses and dwarfed shrubs (Fig. 4-b), with some patterned ground features. Over considerable areas, the forest regeneration has been very poor, good results being obtained only in the northern part of Tuntsa region.

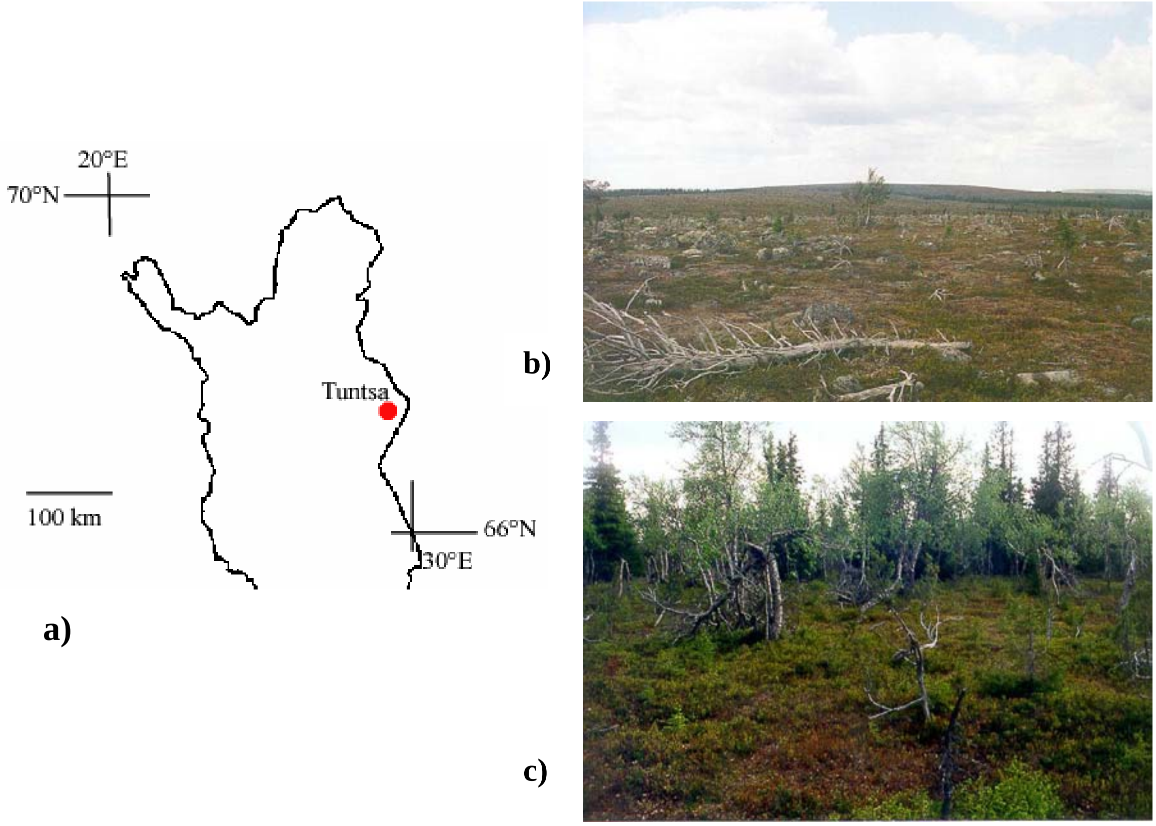

FIGURE 4. (a) Location of Tuntsa in Lapland and (b, c) general overviews of the disturbed site

3.4.2 Field measurements

In order to assess the local climate conditions in the impacted area, meteorological measurements have been carried out since 2003 at Tuntsa on a tundra-covered site and in a Norway spruce-covered fire refuge. Vegetation is the dominant controlling factor of the areal distribution of snow cover (Seppälä 2004). To study the influence of vegetation on the spatial variation of snow depth and density, measurements were performed on a 1 by 0.6 km site with roughly uniform surface, elevation, slope and soil characteristics and with two kind of vegetation: forest and treeless tundra (**Paper III**). The thickness of the snow cover was determined manually (at 126 measurement points) and by radar using an SIR-2000 ground-penetrating radar with a 1000 MHz antenna. Based on these measurements, maps of the spatial distribution of snow depth were prepared applying the Kriging spatial interpolation method with a10 m by 10 m grid size.

In addition, two automatic weather stations were installed in the study area (Fig. 5): one of them situated in the forest, surrounded by Norway spruce (67°38’20’’N/29°51’57’’E, 462 m), the other on a burned-down open site (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 amount of precipitation were measured on an hourly basis in the period September 2003-June 2006. The soil temperature and soil moisture were measured as well, the temperature at three depths (0.1 m, 0.3 m and 0.5 m) and the soil water content at 0.1 m (**Paper IV**). Though gaps occurred in the measurements during the winter season, the data stored could be effectively processed in the study of post-fire heat and water fluxes.

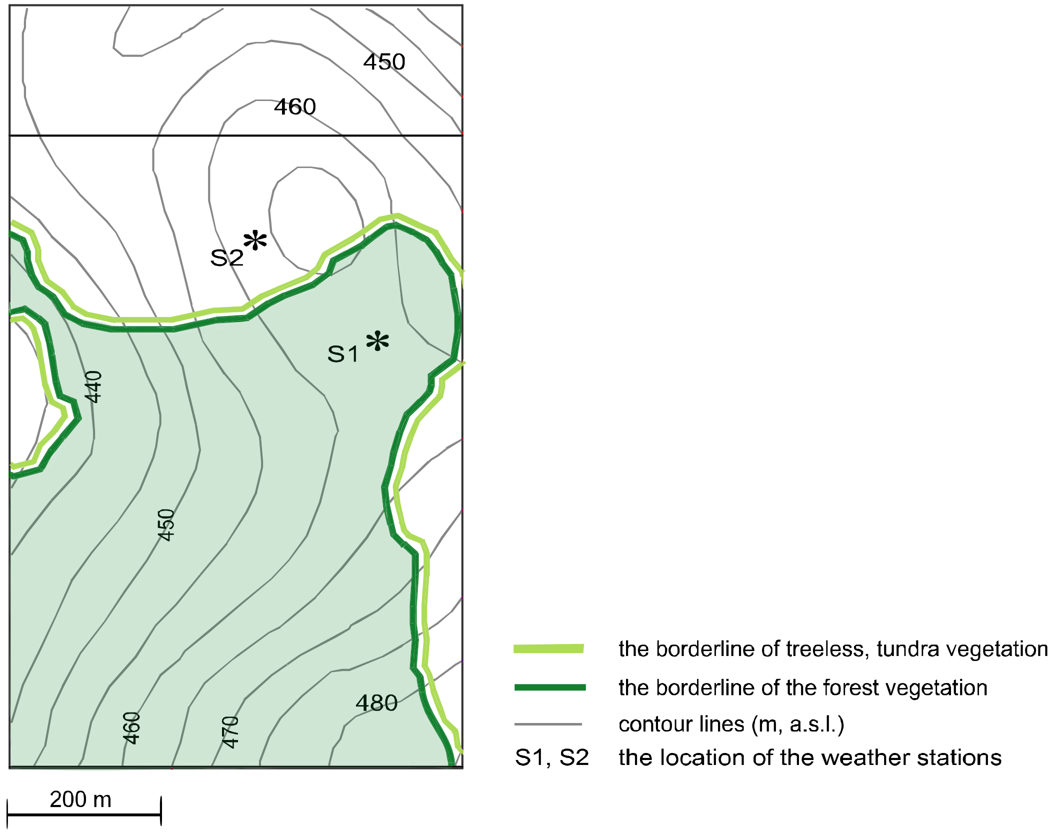

FIGURE 5. The topographic map and the surface roughness of the area studied, and the location of weather stations (*)

3.4.3 Model simulations and data analysis

Wind modelling

Snow accumulation patterns are strongly influenced by wind redistribution, which depends on the roughness of the terrain and vegetation. Since snow drift transport correlates with the wind velocity (Seppälä 2004), a knowledge of the wind climate of the experimental area is crucial in the analysis of snow conditions. As a consequence of the forest fire and the removal of tree mass, the surface roughness has been changed significantly, which in turn has led to increased wind speed and intensified snow drifting. In order to estimate the spatial variation of wind direction and velocity over the study area, a simulation of wind conditions was conducted using WAsP (Wind Atlas Analysis and Application Program, Troen and Peterson 1989), a representative numerical model for the vertical and horizontal extrapolation of wind climate statistics. WAsP incorporates both physical models of the atmosphere and statistical descriptions of the wind climate. It contains several sub-models to describe the wind flow over different terrains and close to sheltering obstacles, e.g., models for orographic flow perturbations, roughness changes and the influence of obstacles on the wind field. The wind climate is described by a Weibull distribution function (Tammelin 1991). A detailed description of the model and the functions used is given in **Paper III**. WAsP has been verified against field measurements and other models, giving in both cases good results (Walmsley et al. 1990, Venäläinen et al. 2003).

Both surface topography and roughness data were given to the model as background information. The roughness lengths of the impacted site were defined based on air photos and surface maps as follows: open field covered by small vegetation, bushes and shrubs (<1.5 m high) with a roughness length of 0.2 m, and forest comprising relatively sparse spruce stands less than 12 m high intermixed with downy birch with a roughness length of 0.5 m. In order to simulate the wind climate of the region measured, the input data were obtained for the winter studied (October 2002-March 2003) from synoptic wind measurements from two representative meteorological stations: Kuusamo Rukatunturi (66°10’N, 29°09’E, 486 m altitude) and Kilpisjärvi Saana (69°02’N, 20°51’E, 1007 m altitude). The selection of the proper stations for providing the input data for the winter wind climate simulations was done taking into account primary criteria such as geographical location, local relief and vegetation, all of which strongly affect the wind characteristics. Unlike the topography of the Tuntsa region, most of the nearby stations are situated at low altitudes (<300 m), mainly in valleys. In addition, the sites of these stations are not covered by tundra-like vegetation. On hilly sites the general wind patterns used for the description of the wind climate should be recorded on the summits to get representative readings (Seppälä 2002). Although Kilpisjärvi Saana is not located within the area studied, it was selected as input in modelling the winter wind climate of the tundra-covered site because of its topography and vegetation. The selected stations have roughly similar surroundings to our experimental site.

As output of the simulations, the mean wind speed and wind speed distribution (Weibull A and k) at a height of 10 metres above the surface were obtained for 10 by 10 m grid squares. For a more substantial analysis, the mean wind speed values were calculated for one location in the middle of the study area at heights of 10 and 2 metres. The wind flow obtained, surface characteristics, vegetation type and snow depth were compared for every grid-square.

Modelling the heat and water fluxes in the soil-vegetation-atmosphere system

In addition, estimation of the annual and seasonal dynamics of the post-fire heat and water fluxes, evaporation, radiation processes and snow conditions of both the open site with tundra vegetation and of the forest was carried out by applying an SVAT model for water and heat fluxes known as COUP (Coupled heat and mass transfer model for soil-plant-atmosphere system, Jansson and Karlberg 2001) described in detail in **Paper IV**. The model is based on the energy balance approach, and simulates one-dimensional water and heat flows in the soil-vegetation-atmosphere system using physically-based algorithms. The COUP model describes a vertical structure of surface compartments and allows for simultaneous water and heat exchange from the vegetation layer and soil or snow surface below (Gustafsson 2002). 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 main equations include the laws of conservation of mass and energy together with a flow equation for heat (Fourier's law) and water (Darcy's law) (Jansson and Karlberg 2001). The driving variables of the model are the climatic data governing the dynamics of the fluxes, e.g., global radiation, mean air temperature, wind speed, precipitation and relative humidity. To solve the water and heat flow equations, a detailed description of soil and plant properties is required. The parameters needed as input in the modelling were based on site measurements, literature values and calibrations against the available observations of soil temperature and moisture content. Simulations were run for the two sites with different surface properties for different periods:

- for the available measurement period (September 2003-September 2004) using the recorded meteorological data
- for a long-term period (1975-2003) applying as driving variables the climate data from the appropriate representative stations
- additionally to the long-term simulations an attempt was made to reproduce the pre-fire and post-fire local climate for the case of a possible forest fire during the simulation period (1975-2003)

The global radiation, mean temperature, wind speed, precipitation and relative humidity were used as driving variables. In the case of long-term simulations, the selection of the wind data was the most difficult, because wind patterns may be affected by local conditions and topography and may change significantly within a restricted area. Estimates of the wind data have been made using the measurements from two stations located close to our experimental site: Kuusamo Airport (65°59'N, 29°13'E, 264 m altitude) for the tundra-covered area and the FMI Arctic Research Centre at Sodankylä (67°22'N, 26°37'E, 179 m altitude) for the spruce forest. A previous comparison of wind measurements from the selected stations and on-site observations confirmed the applicability of the data in question.

The wind speed has been calculated using the logarithmic wind profile:

$$u_z = \frac{u_*}{k} \ln\left(\frac{z}{z_0}\right) \qquad (3)$$

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.

The air temperature, relative humidity and precipitation values from the closest meteorological station at Salla Värriötunturi (67°45’N, 29°37’E, 370 m altitude) were applied, while the global radiation data was taken from the Arctic Research Centre at Sodankylä (67°22`N, 26°37’E, 179 m altitude). The soil and vegetation parameters were defined based on site observations and the literature.

Based on direct measurements of the local climate conditions and the modelled energy and water fluxes over the fire-disturbed area and forest-covered fire refuge, the effect of the altered surface on local climate and its feedback on vegetation recovery were evaluated (**Papers III** and **IV**).

4. RESULTS AND DISCUSSION

4.1 The influence of geographical factors on the spatial variation of climate in Finnish Lapland

The statistical analysis of the temperature-based climatic parameters in relation to the influence of natural variables on regional climate indicated a strong dependence of mean and daytime maximum temperature (correlation coefficients 0.97 and 0.99) on geographical conditions. On the other hand, the night minimum temperature had a weak correlation with the natural factors (0.50).

Considering the effect of each geographical factor in particular, we found that the latitude and local relief, i.e., elevation, have a significant influence on regional climate (the correlation coefficients for the summer mean temperature was 0.80 and 0.56, respectively), while the longitude, sea and lakes do not play an important role in shaping the climate of Lapland on a regional scale (respective correlation coefficients obtained from the same test: 0.07, 0.13 and 0.03). Nevertheless their effect, particularly of large water bodies on a local scale, is traceable (**Papers I** and **II**).

The spatial variation of summer mean temperature based on measured data and interpolations including various “external forcing” variables demonstrates the role of these factors in forming the climate of the area studied (Fig. 6). The interpolations were done applying the 1 km spatial resolution Kriging method, run without lake-coverage or elevation, and using only the latitude. The spatial variation including only the coordinates (Fig. 6-d) gives a very coarse distribution of temperature with a uniform decrease northward. The inclusion of the lake component (Fig. 6-c) improves only slightly the spatial variation, accentuating the warming effect – of 1 °C – of the larger lakes (Lake Inari, the Lokka and Porttipahta reservoirs, Lake Kemijärvi and Lake Yli-Kitka). The simulation excluding the lake components, but including the relief and coordinates showed roughly the same spatial variation of temperature as the run including all “external forcing” parameters (Fig. 6-b). Contrary to previous studies, which indicated a significant warming effect of lakes on the regional climate of Fennoscandia (Laaksonen 1976b, Solantie 1976), especially for the mean and minimum air temperature, we have not found a similar effect based on the stations studied. This small-scale effect of inland waters is likely to be due to the low amount of lake coverage in Lapland compared to the southern part of Finland. The northernmost-situated lakes, the Inari basin particularly, have a close connection with the Arctic Ocean because of the lack of a topographic barrier in the NE (Seppälä and Rastas 1980). Under this influence, Lake Inari and the Lokka and Porttipahta reservoirs are covered by ice for about 210-215 days per year (Atlas of Finland, Water 1986). The lake influence appears in July, after the complete melting of the ice and snow, and intensifies toward autumn, showing up as a warming of 1.5-2 °C at stations situated by the lakes. The warming effect of the lakes declines in October to December depending on the size and depth of the lakes (**Paper I**).

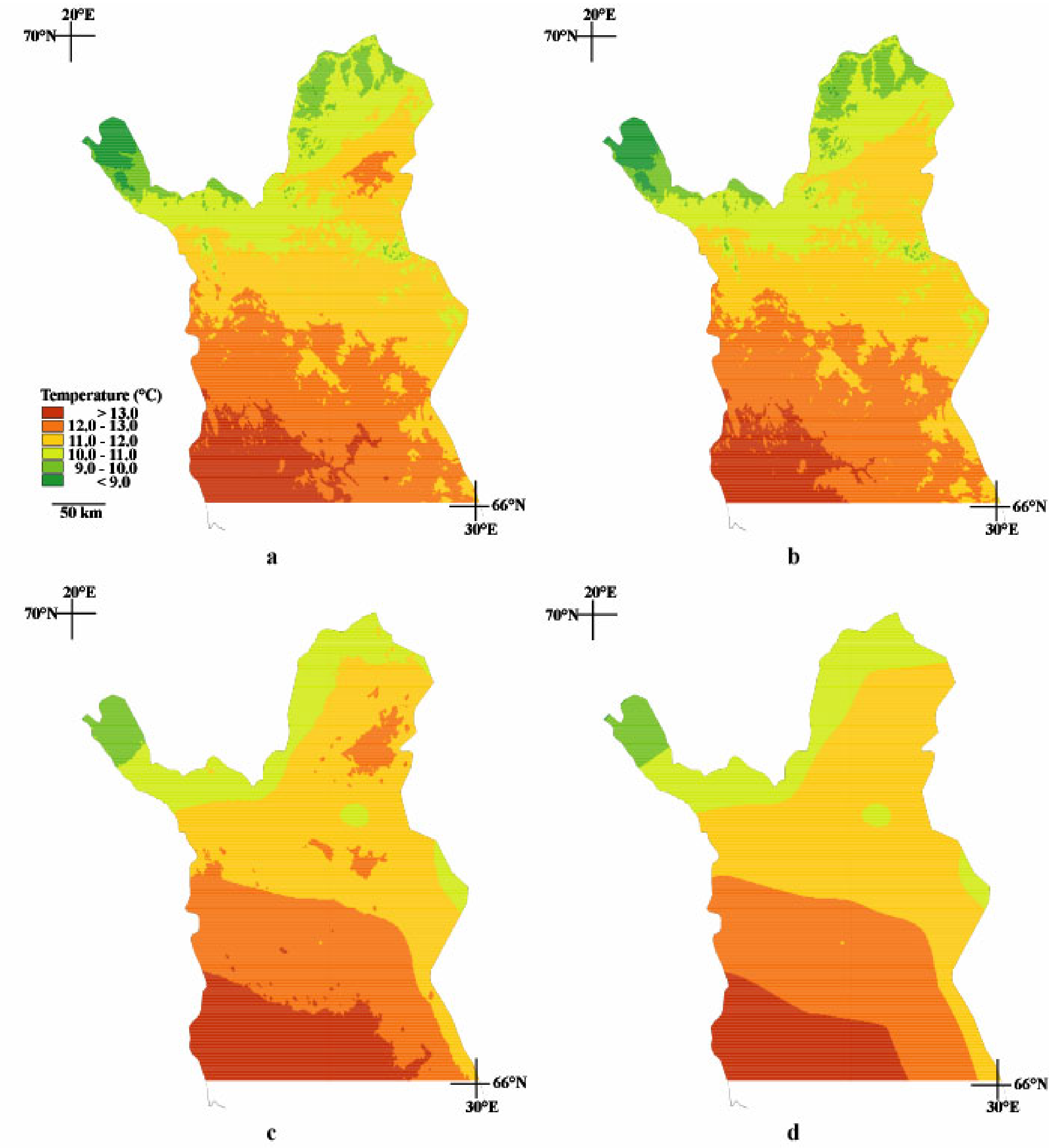

FIGURE 6. The spatial variation of summer mean temperature based on: (a) measured data, (b) interpolation excluding the lake-coverage parameter, (c) interpolation excluding the elevation parameter and (d) interpolation using only co-ordinates

Continentality is more intense in Lapland than in the southern and central parts of Finland (Tveito et al. 2000). As the results of **Paper I** indicated, the maritime influence is not significant, being limited only to the northernmost-situated areas, determined by the effect of the Atlantic Ocean, whose Gulf Stream makes the climate milder (**Paper II**). Similar results concerning the effect of the oceans on the climate of Lapland have been reported by other authors (Laaksonen 1976b, Tveito et al. 2000, Autio and Heikkinen 2002, Tikkanen 2005).

The difference in the amount of incoming and outgoing radiation, as well as the small amount or total lack of solar radiation in the wintertime, together with the snow and ice conditions at high latitudes, are the main causes for the linear decrease of temperature from south to north. According to the results, latitude induces a decrease of 0.66 °C per degree of latitude for the annual mean temperature in Lapland. The elevation, along with the local relief and the exposure of the slope, produces the local characteristics of the climatological elements. In addition, during clear, calm summer nights or cold periods in winter, the development of a ground surface temperature inversion occurs frequently in valleys, affecting the surrounding hills and fells (Autio and Heikkinen 2002). In these conditions the temperature difference between the valley bottom and the inversion peak on the surrounding upper slope can be 10-20 °C.

The altitude of the stations used in our study ranged between 35 and 480 m. Based on measurements from these stations, we found a vertical gradient of 0.61 °C/100 m for the annual mean temperature, with 0.23 °C/100 m for the wintertime mean and 0.58 °C/100 m for the summer mean temperature. These results are consistent with those of previous work concerning the influence of latitude and elevation on climate in Fennoscandia (Laaksonen 1976a, Tveito et al. 2000). Laaksonen (1976a) reported a decrease of annual temperature of 0.49 °C per degree of latitude for Fennoscandia and a vertical temperature gradient of 0.4-0.6 °C/100 m based on a large selection of stations between sea level and 2062 m. Similarly, studying the temperature variation in the Nordic countries, Tveito et al. (2000) reported a latitude-induced temperature variation of 0.19-0.44 °C per degree of latitude gradient, and a vertical temperature gradient of 0.1 °C/100 m in the winter and 0.6° C/100 m in the summer months.

4.2 Small-scale spatial variation of temperature and precipitation in Finnish Lapland

According to the Köppen-Geiger-Pohl climate classification, northern Finland belongs almost entirely to an area of snow and boreal forest climate with short summers and damp, cold winters, covered by boreal forest, while the northernmost part is situated in the tundra zone of an ice climate, characterised by very short summers (Essenwanger 2001, Tikkanen 2005). The climate of Finnish Lapland is described through a set of high spatial resolution maps (1 by 1 km) of temperature-derived parameters and precipitation, presented in detail in **Paper II**. Although the spatial variation of climate in Finland has been described in several earlier studies (Laaksonen 1976, 1977, Atlas of Finland-Climate 1987, Tveito et al. 1997, 2000, 2001, Solantie and Drebs 2001), our research was conducted using more recent input data and on a higher resolution (1 km) thus providing a more accurate description of the local and regional features, despite the scattered observation network. In addition, local geographical factors, such as coordinates, elevation, lake and sea coverage were also taken into account in order to improve the description of the variables.

Temperature

The spatial distribution of the temperature-based parameters showed latitudinal dependence, including some local patterns determined by the topography and the proximity of water bodies. The mean annual temperature ranges from 1 °C in the SW region, close to the coast of the Gulf of Bothnia, to -3 °C in the NW, in the Scandinavian mountain range (Kilpisjärvi) and the western part of fell Lapland (Palojärvi). The 0 °C isotherm runs in an east-west direction close to the stations of Pello, Meltosjärvi and Rovaniemi (Fig. 7). The temperature-derived maps, such as those showing the duration, beginning and end of the frost-free and growing periods, indicate the most favourable temperature conditions to be in the lower part of the Kemijoki basin and around the large lakes (Lake Inari and Lake Lokka). This spatial feature, especially in the case of the frost-free season, is the result of the compensatory and heating role of water during the cold season. Proceeding towards the northeast, the length of the growing season gradually decreases. The spatial distribution of available heat for plants during the growing season obtained for the 1971-2000 period indicated similar conditions for plant growth and development in Northern Lapland as those estimated in earlier works (Tveito et al. 2001) based on the normal period (1961-1990). However, the length of the frost-free and growing season seemed to differ in the two periods, the deviations being produced by differences in definitions and computation.

The presence of the centres of continentality during September-March over eastern Finland and Lapland, as well as the cold airstreams in early summer originating from the ice fields of northern Eurasia are the main shaping factors of the above-mentioned spatial features (Pulliainen 1987, Solantie 1990). Due to their location and topography, the coldest area of Lapland is likely to be the fell areas and Kilpisjärvi together with the surrounding hills (**Paper II**). Despite of its northern location, the Inari region has a warmer climate than the surrounding area, due to the influence of Lake Inari and of the Arctic Ocean, which is kept open by the Gulf Stream; thus, the winter temperature is relatively high on the coast (Tikkanen 2005). Due to the lack of solar radiation, ground temperature inversions tend to develop over the fell areas during midwinter. Such a temperature inversion evolves during calm and clear weather in a high pressure area, and may last unbroken for several days, weeks or even more than a month (Huovila 1987). Under these conditions, large differences may be observed in the temperature records of two neighbouring stations (**Paper II**). Since many of the meteorological network stations are situated low down, e.g., in valleys, the integrated mean temperature of cold winters on hills and in mountainous areas may be warmer than the temperature records indicate (Huovila 1987). On the other hand, the temperature inversions can also cause vegetation damage by rapid temperature fluctuation and night frost during the growing season or summer (Autio 2006).

According to the variation of diurnal temperature range (DTR, defined as the difference between the maximum and minimum temperature for any given day), the most oceanic area is the northernmost part of Lapland, where the influence of the Arctic Ocean is felt most prominently. Reduced DTR values were also observed in the Kilpisjärvi region, determined partly by the maritime effect but also by the local topography of the station.

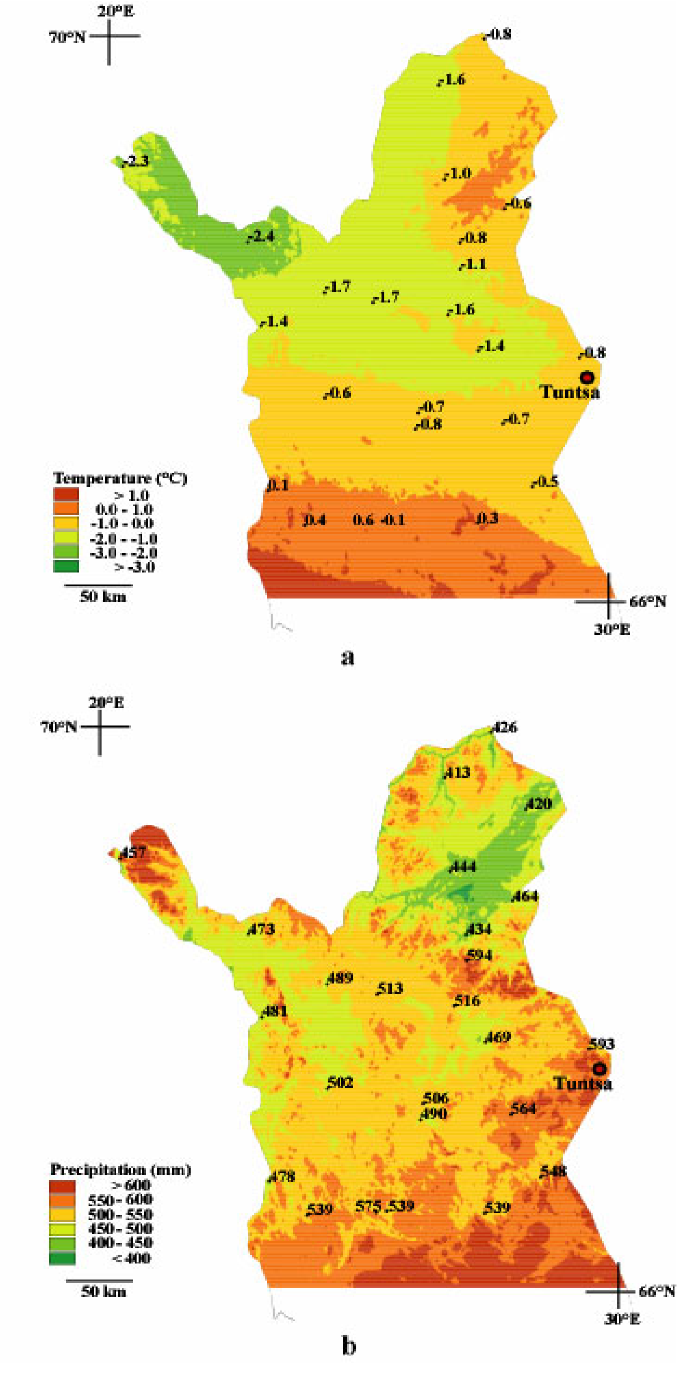

FIGURE 7. (a) The annual mean temperature and (b) the precipitation sum for the period 1971-2000

The climate is most pronouncedly continental in the inland district, i.e., in the Kemijoki and Saariselkä regions, where the minimum temperature during the winter can occasionally drop below -50 °C (the lowest temperature recorded during the 20th century was -51.5 °C at the Kittilä Pokka station), whereas it can rise to above 30 °C during summer months. The spatial distribution of the annual range of mean temperature during 1961-1990 (Heino 1994) showed similar features for the continentality and maritime effects.

Precipitation

Finnish Lapland receives generally less precipitation than the rest of Finland. The spatial distribution of precipitation shows both a latitudinal and a longitudinal dependence, including also the influence of particular local features, such as rain-shadow and elevation (**Paper II**). The foehn effect generated by the Scandinavian mountains lessens the amount of precipitation in north-western Lapland (450-500 mm). After crossing the Scandinavian mountain range the Atlantic air masses become dry and warm, raising the temperature and reducing the rain amount on the leeward slopes. The number of rainy days, as well as the annual precipitation increases eastward (up to 600 mm). Precipitation is lowest in the Inari basin and along the Utsjoki valley (Fig. 7). Although in the southern and south-western part of Lapland the number of rainy days is somewhat reduced, the annual sum of precipitation is substantially higher than in other parts. This discrepancy might be caused by two factors: (1) the warmer air situated over central Finland and the southern part of Lapland can hold more moisture than the cooler air over the northern region and (2) the SW-NE route of the depressions that bring precipitation to Finland. Our results confirm the spatial variation of annual precipitation amount for 1961-1990 (Heino 1994, Tveito et al. 1997). Nevertheless, the maps prepared with high spatial resolutions allow a more profound presentation and analysis of climatological parameters.

4.3 Character of the local climate on a fire-disturbed site at the northern timberline

4.3.1 Temperature, precipitation and wind components

The altered local climate conditions of the fire-disturbed environment in the Tuntsa area, located near the climatological limit of forests, were determined based on the measured and modelled heat and water fluxes (**Papers III** and **IV**). Since local measurements cover a three-year long period, we have extended the analysis comparing modelled data for a period of 28 years in order to obtain more relevant results about the local heat and water fluxes.

Differences in daily mean, minimum and maximum temperatures, solar radiation, relative humidity and precipitation on the treeless tundra vegetation and in the Norway spruce forest were reduced. The mean air temperature variation was of the order of 0.2 °C between the two sites during the measured period, while the global radiation was reduced by only 20% (**Paper IV**). These results partially contradict those of previous studies, concerning the variation of the above-mentioned parameters. Studies from Canada (Chen et al. 1993, Carlson and Groot 1997, Spittlehouse et al. 2004) and Sweden (Karlsson 2000) reported warmer conditions over the clearing during the day and a difference of

0.6-0.7 °C in magnitude, attributable to the fact that the forest canopy reduces the diurnal temperature range compared to open areas. Precipitation reaching the ground can be reduced by 10-30% due to interception by the forest canopy. Nevertheless, this contrast depends particularly on the size of the clearings and the density of the forest. In the case of the Tuntsa area, the forested sites consist of sparse spruce stands intermixed with rich ground vegetation. This low canopy density allows an ample amount of precipitation and solar radiation to reach the undergrowth or the forest floor.

The removal of tall vegetation from the affected site resulted in a significant increase in wind velocity (**Papers III** and **IV**). According to the modelled winter wind climate (Fig. 8-a) and the measured wind data during the frost-free season (Fig. 8-b) , the altered surface roughness induced a 60-70% stronger wind over the open site compared to the spruce forest, and doubled the probability of a high wind speed. The highest hourly wind speed recorded in the forest was 11 m/s, while in the open it was 15 m/s. The spatial distribution of the modelled average wind speed on the site studied confirms the dependence of wind pattern on vegetation (**Paper III**).

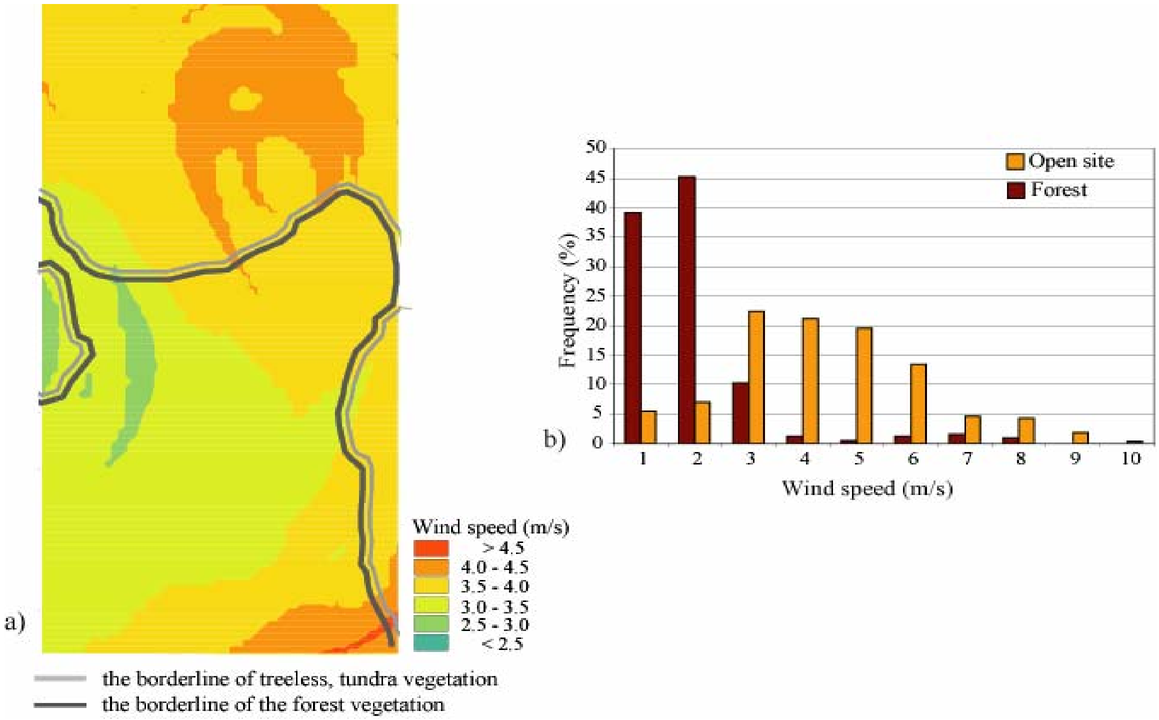

FIGURE 8. (a) The spatial variation of simulated mean wind speed for October 2002-March 2003 and (b) the relative frequency distribution of the mean wind speed measured at 3 m above the surface during the frost-free season in 2005-2006

Wind flow velocity is an essential factor in snow accumulation, which in turn may directly or indirectly affect plant development by assuring protection against desiccation and wind abrasion, reducing the soil frost, increasing the soil moisture content and by affecting the nutrient release. Additionally, increased wind speed can have both mechanical and physical effects upon plants, i.e., impact on stomatal conductance, abrasion of the cuticular vaxes, and desiccation of trees' foliage (Van Gardingen and Grace 1991, Heikkinen et al., 2002).

4.3.2 Snow cover

Snow cover, which is of great importance to site conditions and seedling establishment, varies widely on account of topography, exposure, altitude, vegetation cover and land surface roughness (Clark et al. 1985, Holtmeier et al. 2003). Our measurements indicate that the distribution of snow accumulation varied in relation to the type of vegetation and wind velocity (linear regression coefficient 0.90), while the influence of elevation was less demonstrable (correlation coefficient: 0.17) because of the flat features of the experimental site.

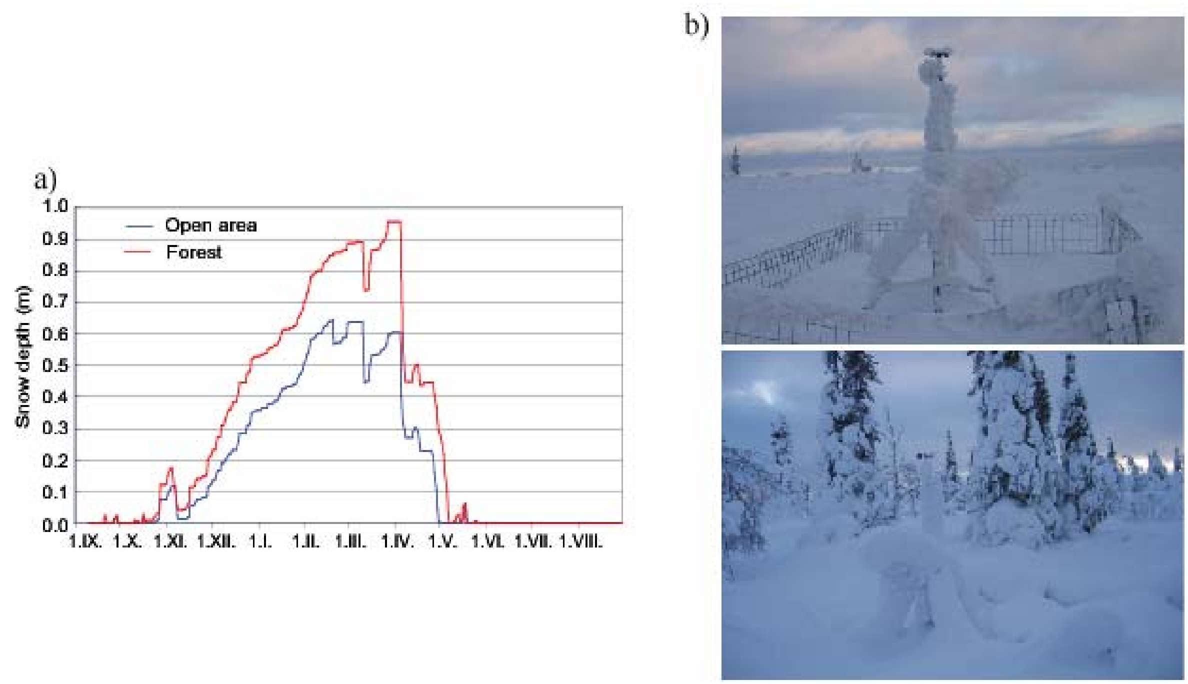

FIGURE 9. (a) The simulated snow depth for tundra vegetation and the forest, September 2003-May 2004, and (b) general overviews of the snow-covered stations in February 2005

Concerning the small-scale (10 by 10 m) spatial variation of the snow cover over the site, the lowest snow depths were measured over the tundra-covered clearing, where the high wind velocities allowed vigorous snow drifting (40-70 cm snow depth). In the forest, the snow thickness turned out to be 30-50 cm deeper, varying from 70 to 120 cm (Fig. 9). The frequently-occurring strong winds and snow blowing over the open area led to snow redistribution and its redeposition at the forest boundary, where the snow depth reached its maximum, 140 cm (**Paper III**).

The differences in vegetation repartition have also given rise to a much higher water equivalent in the forest compared to the treeless site. Furthermore, the thin snow cover on the clearings is appreciably compacted and hardened compared to the soft snow cover in the forests (Autio 2006), as was also the case on the site studied. The canopy effect in the forest and the varying snow distribution through the two vegetation types result in a more rapid snowmelt on the open area (**Paper IV**), leaving the ground bare, while in the forest it is normally delayed by about 6-12 days (Fig. 9). Snow-vegetation interactions are two-sided: besides the influence of vegetation on snow distribution and accumulation, the feedback of snow cover to vegetation and ecological, hydrological processes is obvious. The variations in snow depth and density in the area studied trigger significant differences in the energy and moisture interactions over the two surface types. Deeper, more insulative snow results in higher subnivian temperatures that in turn augment decomposition and nutrient mineralization in winter, producing more favourable growing conditions and increases in spring runoff and winter CO_2 emission (Sturm et al. 2001). Moreover the thick snow cover protects the vegetation from winter desiccation and wind abrasion, reduces frost activity and increases melt-water production and summer soil moisture (Seppänen 1961, Liston et al. 2002). On the other hand, a heavy snow load and the formation of rime and hoar frost on trees may cause severe damage to the vegetation. Trees in Lapland tend to be covered by a combination of snow, rime and hoar frost every winter (Jalkanen and Konopka 1998). Rime and hoar frost form on the windward side of tree branches, plant stems and other objects (Fig. 9), producing large deposits of ice (Seppälä 2004). The increased mass of ice and snow accumulation can break the tree crown and branches, particularly in elevated terrain, affecting the situation of the altitudinal and northern timberline (Heikkinen et al. 2002).

4.3.3 Soil temperature and moisture

The variation in surface and soil temperature (at depths of 0.1, 0.3, 0.5 m) as well as that in soil moisture (at a depth of 0.1 m) was relevant, and verified the remarkable influence of the surface conditions. The interception of 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 forest refuge absorbed a larger fraction of radiation, and substantially reduced the irradiance of the soil surface. Furthermore the increased moisture content of the mineral soil has a strong influence on the insulating effect of the surface, resulting in a decrease of soil temperature (Bonan 1989, Redding et al. 2003). In time, as vegetation starts to return to the disturbed clearings, the canopy of the new vegetation moderates the differences in soil and moisture content (Amacher et al. 2001, Carlson and Groot 1997).

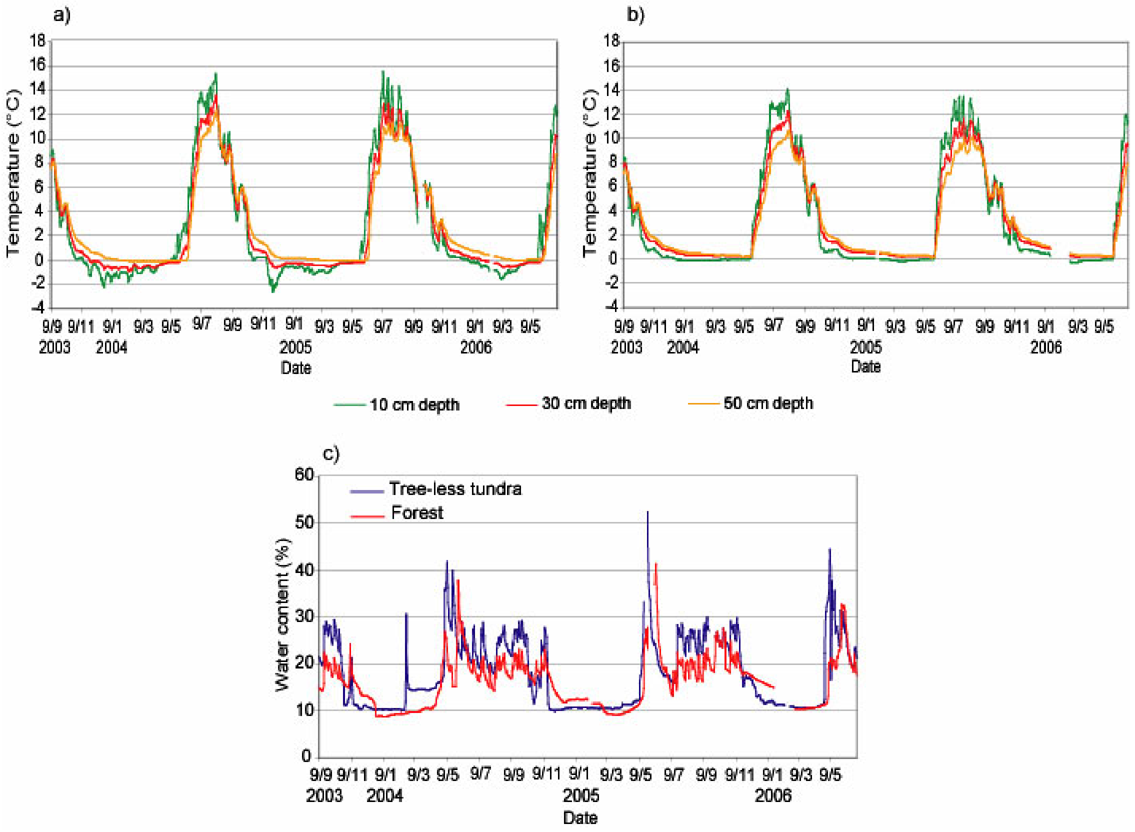

FIGURE 10. The variation of mean soil temperature at depths of 10 cm, 30 cm and 50 cm beneath (a) the tundra vegetation and (b) forest; (c) the soil moisture at a depth of 10 cm from September 2003 to June 2006

Due to the protecting feature of the vegetation and to the thicker snow cover (**Paper III**), the temporal variation of soil temperature on the sites differed significantly (indicated by the applied t-test): the variation of soil temperature was moderated in the forest and the depth and length of the soil frost was reduced (**Paper IV**). Recording an annual amplitude of 4.8 °C, the soil surface temperature had a more pronounced fluctuation on the short-vegetation-covered site than on the tree-covered site (Table I). Soil temperatures were higher at the open site during summer compared to the forest, while this trend was reversed during the winter, when the soil frost occurred earlier and was more intense on the open site than in the forest. During winter the thick snow cover in the forest had strong insulating properties, holding the soil temperature above freezing (Fig. 10).

TABLE I. Variation of soil temperature and water content at the study site from September 2003 to June 2006

	Measurement period (September 2003-June 2006)											
	Soil temp. 0.1 m (°C)			***Soil temp. 0.3 m (°C)***			***Soil temp. 0.5 m (°C)***			***Soil water content 0.1 m (%)***		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
Tundra	2.5	15.6	-2.6	2.4	13.6	-0.9	2.6	12.4	-0.1	17.9	52.6	10.0
Forest	3.0	14.1	-0.3	3.1	12.3	0.1	2.9	10.7	0.1	16.1	41.4	8.7

(cont'd)

	Growing season			
	Cumulative soil temp. (°Cd)			***Average soil moisture (%)***
	0.1 m	0.3 m	0.5 m	0.1 m
Tundra	465.5	375.9	311.6	22.0
Forest	429.1	337.4	252.6	18.2

The major differences in the soil temperatures measured at the two sites occurred in the extreme values and the cumulative soil temperature during the growing season (40-60 °C d), which is particularly important for tree growth.

Soil moisture depends highly on the characteristics of the soil, i.e., its texture and hydraulic properties, but also on the structure of the vegetation. In general, the largest variations in soil moisture were registered in the topsoil, which had higher values during the warm season and the other way round during the winter (a difference of 5-10%). In the deeper layers, the differences between the two soils were less pronounced, although in the long run the soil from the forest seemed to be slightly moister (**Paper IV**). The canopy and the dense ground vegetation in the forest catch a fraction of the precipitation, hereby precluding excessive moisture supplementation. The presence of the canopy and ground vegetation also serves to protect the soil from desiccation. Unlike in the forest, the soil on the low vegetation site was more receptive to variations in precipitation during the warm season and variations in temperature in wintertime. The soil water content of the upper soil layer generally increases following clearcutting or fire events, as a result of the decreased evapotranspirational demand (Gray et al. 2002, Redding et al. 2003). The peak in the soil water content level occurred in spring, during the snowmelt, with a time lag of about 20 days in the spruce forest.

4.3.4 Evaporation and energy fluxes

Energy partitioning is particularly sensitive to the proportion of solar radiation that reaches the surface and is available to drive sensible and latent heat exchange (Jarvis 1997, Baldocchi et al. 2000, Eugster et al. 2000). Changes in land-surface properties associated with canopy complexity, induced by fires or increased logging in forested areas, may substantially alter energy and water exchange in the transitional region between forest and tundra vegetation (Eugster et al. 2000). The high leaf area index (4-4.5 m^2 m^{-2}), tall stands (9 m), deeply-rooted trees in the spruce forest in contrast to the low leaf area index (0.5-1 m^2 m^{-2}), short (0.1-0.2 m), shallow-rooted grass and shrub vegetation are determining factors in the amount and repartition of energy fluxes. The amount of evaporation was persistently higher over the spruce forest than on the treeless site, the former exceeding the latter by 48% (for 1975-2003). The spruce stands evaporated on average over 360 mm y^{-1} of water, while the low, tundra vegetation evaporated over 190 mm $y^{-1}$of water (**Paper IV**). The indicated values match reasonably well with those from previous studies (Budyko 1974, Baldocchi et al. 2000) which reported a range of evaporation between 300 and 400 mm y^{-1} for boreal forests.

The partitioning of evaporation components confirms the dominance of transpiration and interception evaporation from the canopy and the rich understorey vegetation on the forested site (92% of the total evapotranspiration). Contrary to the forest, over the open site soil evaporation contributes the most significant fraction (55%) of the total evaporation. This is explained by differences in the development of the leaf area, canopy surface resistance and the higher interception storage of the forest. As leaf area is increased, shading of the ground may strongly impede soil evaporation but at the same time transpiration may increase (Beringer et al. 2005).

Soil moisture has been considered one of the most important factors in controlling the evaporation over different vegetation types in the arctic ecosystem, such as open forest, tundra or dry heath (Lafleur 1992, Lynch et al. 1999a, Lynch et al.1999b, Baldocchi et al. 2000, Oltchev et al. 2002). Similarly, there was a stronger correlation between the daily evaporation and daily average of volumetric soil moisture content of the soil on the tundra covered site (r=0.60) than in the forest (r=0.44). This difference may be due to the poor exposure of the ground surface in forest and the difference in vegetation cover density of the two sites. The seasonal variation of evapotranspiration is controlled particularly by changes in soil temperature and soil moisture, radiation, atmospheric humidity and leaf area. Peak values of evapotranspiration occurred between May and August.

The repartition of the amount of energy used in latent heating (evapotranspiration) and sensible heat flow varies on the two sites, latent heat fluxes accounting for 43% of the total energy fluxes in the forested area and only 31% on the open site (**Paper IV**). During May-August, the important season for plant development, latent heating showed values higher by 8-14 W m^{-2} in the forest, taken over the period 1975-2004. Likewise, the sensible heat flux from the forest exceeded that from the low vegetation in every season. According to the simulated values, the summer-time sensible heating increases as the vegetation becomes denser, registering a difference of 5-60 W m^{-2} between the two sites during May-August. The ratio of sensible heat to latent heat increases from tundra (0.4) to forest (0.8), indicating the increasing dominance of sensible heating as an energy source for the atmosphere in the case of the latter.

4.4 Feedback of the changed local and regional climate on surface and vegetation

Climate-disturbances-vegetation interactions are particularly important at high latitudes, as any changes in vegetation and surface may produce a large feedback into the local climate. The changed climate and the altered surface conditions may in turn create negative feedbacks to the ecosystem, preventing the vegetation from returning to its original state (Bonan et al. 1992, Lynch et al. 1999a). Following the widespread forest fire in 1960, the reproduction of boreal vegetation in the Tuntsa area has repeatedly failed, despite attempts at regeneration with Scots pine. According to our measurements and heat and water flux simulations, the climate and physical site conditions became more severe as a consequence of the fire, impeding the re-establishment of forest. Although the development of tundra-like vegetation mitigated the extremes in variations of fluxes compared to those from the barren post-fire surface (**Paper IV**), the local climate on the two types of vegetation still differs significantly.

It is known that near and at the timberline and tree-line the growth of trees reacts very sensitively to the annual climatic variations and also to long-term fluctuations (Hustich 1983), and thus the recovery times after fires are longer, particularly during climatically unfavourable periods (Kullman 2005a). Regeneration of tree vegetation requires suitable environmental conditions, such as a beneficial temperature and light quality, sufficient, but not excessive soil moisture, especially for early seeding survival, and reduced soil frost during winter. At the same time, the annual variation of temperature is more relevant for the growth process of trees than is the variation in precipitation (Hustich 1983). In order to achieve successful regeneration, favourable climatic conditions must prevail for several years (Timonen and Varmola 1985, Tasanen et al. 1998, Sveinbjörnsson 2002). The total temperature sum for the summer (threshold value of 5°C) required to result in 50% of Scots pine seed maturing should be at least 845 degree-days in Lapland (Pohtila 1997) and about 700-800 degree-days for Norway spruce (Almqvist et al. 1998 as cited by Juntunen and Neuvonen 2006). During the period 1971-2000, the effective summer (May-September) temperature sum at the closest weather station (Salla Värriötunturi) varied between 495 d.d. and 846 d.d., with an average of 648 d.d. During the growing season the temperature sum in the Tuntsa region ranged between 450-500 d.d. (**Paper II**). This implies that the required temperature sum for the recovery of trees has not been reached; there were also several cold periods (for example 1975-1978) when the summer temperature sums were well below the average. The reduced temperature sums and the short growing season (60-70 days), in association with occasional night frost during the growing season may reduce seed germination, increasing seedling mortality and reduce the development of buds (Autio 2006). Up to half of the original seedlings may die as a result of unfavourable natural conditions. High seedling mortality under severe climatic conditions might constitute the decisive obstacle in vegetation recovery close to the timberline and tree-line (Hustich 1966, Pohtila 1997, Tasanen et al. 1998).

In addition, a thin or absent snow cover, deep frozen soil, ice particle abrasion, strong winds and water stress due to eroded soil all impede the establishment of seedlings (Sirois 1993, Holtmeier et al. 2003, Autio 2006). The accumulation of snow, and the microclimatological conditions induced by variations in the snow cover, may cause differences in growth conditions. Deep, insulative snow assures greater protection from winter desiccation and wind abrasion by snow and ice crystals, reduces frost activity and increases snowmelt runoff and summer soil moisture (Seppänen 1961, Sturm et al. 2001), while a thin snow cover reduces the winter insulation, allowing the penetration of cold air into the soil, reduces the length of the frost-free season and modifies the energy balance (**Paper IV**). This in turn will induce deep freezing temperatures, causing damage to shallow seed roots (Holtmeier et al. 2003). In this way, the reduced snow depth on the treeless area (**Paper III**) may also impede seed establishment and growth on the site. Furthermore, the thin snow cover allows the large number of reindeer herded in the region - 12 080 a year (Kemppainen et al. 2001) - to destroy sprouts and retard shoot formation. Clear-cut areas and other treeless areas, as well as young forests, are favoured by reindeers from the beginning of summer until late autumn (Colpaert et al. 2003).

It is generally recognized that the exposed soil surface after a fire constitutes a particularly good germination substrate for both Norway spruce and Scots pine (Sirois 1993, Bradshaw 1993). The warmer surface and soil conditions on the low-vegetation-covered site during summer (**Paper IV**), especially in the growing season (Table I), could be favourable for vegetation growth. However, the excessive soil evaporation and the lack of organic matter may induce moisture deficiency during dry periods and hamper mineralization (Holtmeier et al. 2003). Limitation in nutrients may be another obstructive factor in these northern conditions, although soil preparation on regeneration sites is essential and very effective in promoting tree seedling growth (Pohtila 1997, Zackrisson et al. 1997). The changes in wind climate and energy fluxes on the fire-affected site may also contribute to the failed regeneration (**Papers III** and **IV**). Physical and mechanical processes, like abrasion of cuticular vaxes (Van Gardinger and Grace 1991), wind-induced damages of young trees, i.e., needle damage and needle loss and mechanical stress on the branches all induce a climatic stress for tree regeneration.

Despite several cases of new regeneration near the actual timberline and tree-line in Finnish Lapland (Autio 2006, Juntunen and Neuvonen 2006), and an advance of the actual timberline as a result of climate warming (Juntunen et al. 2002), physical, climatological and topographical constrains may occur that hinder the regeneration of vegetation, shifting the timberline southwards. Following the Tuntsa forest fire, since 1960 periods have been reported with favourable regeneration conditions in Lapland. Furthermore, previous research has shown that the regeneration period required for a clearing to be converted to a stand of young pine is on average 30-40 years (Pohtila 1997). Even so, a substantial area of the damaged site is still unforested. Although we have focused mainly on the changed local climate and less on the ecological aspect of the species recovery, it is very likely that the changed climatological and environmental conditions have had a negative feedback on boreal forest recovery. On the other hand, we do not exclude the possible influence of other factors that might exacerbate the poor regeneration; these include the poor quality of the soil, as the area is a barren watershed, the high intensity of the fire, the complete excision of the damaged trees, the partly southern origin of the planting material and the use during one summer of a growth hormone for disinfection, which killed sprouting (Haataja 1993).

It has already been shown that climatic fluctuations, unsuitable seed origin and other factors may cause partial or total failure of reforestation in Lapland (Timonen and Varmola 1985, Pohtila 1997). In addition, it seems that pine seedlings are more predisposed than spruce to different kinds of weather damage, resulting in higher seedling mortality and poorer regeneration (Tolvonen and Kubin 1990, Juntunen and Neuvonen 2006). Regeneration experiments in Lapland have shown that pine succeeded better in lower, sheltered areas with favourable temperature conditions, while the survival of spruce was greater on top of hills (Tolvonen and Kubin 1990). Concerning the effect of fires and forest regeneration, it has also been shown that seed beds that suffered a moderate burn provided a better survivor environment for post-fire recovery (Sirois 1993). Unlike the poor regeneration on the Finnish side of the burned area, the forest recovery was abundant on the Russian side. This implies that the changed local climatological conditions, the intense logging of damaged trees after the fire and the excessive reindeer husbandry have produced more unfavourable conditions for the reproduction of boreal vegetation, causing deviations in the regional position of the timberline.

Similar reduced post-fire tree regeneration in the boreal-subarctic ecosystem has been reported for the Canadian Arctic treeline as well (Sirois and Payette 1991, Arsenault and Payette 1992, 1997), where the absence of post-fire regeneration changed the vegetation cover in the former boreal forest towards forest-tundra and lichen-tundra.

Although unfavourable topoclimatic characteristics have negatively affected tree growth and recovery, the position and composition of the timberline and tree-line may also benefit considerably from present and future changes in climate. Changes in tree establishment and growth, and advance of the actual timberline have been occurring in many locations due to a series of warm summers and mild winters (Juntunen et al. 2002, Kullman 2005a, Kullman 2005b, Autio 2006). Although the mean temperature indicated cooling in Lapland compared to the first normal period (1931-1960), the climate became warmer again during the last part of the 20th century. The increase in annual temperature, especially in winter and spring (**Paper II**) benefits tree growth by prolonging the growing season and the heat available for plant development. Temperature, however, is not the only regulating factor for the location of the timberline; precipitation, particularly during the growing season, the amounts of light and nutrients, carbon dioxide deficiency, topography, soil conditions and biological impacts are also causal factors in timberline formation (Heikkinen et al. 2002, Autio 2006). The precipitation regime has also shown changes for 1971-2000 compared to 1931-1960, manifesting in an increase in precipitation amount an in the number of rainy days (**Paper II**), which also foster tree growth and thereby the advance of the timberline northward and upward. On the other hand, the observed and the projected changes may trigger climatic stress and, indirectly, physiological stress that may slow down the responsiveness of the timber- and tree-line to climate change (Grace et al. 2002, Juntunen et al. 2002, Kullman 2005a). Due to warming, the snow cover becomes thinner and melts earlier in spring, leading to severe and prolonged ground freezing (**Paper IV**), frost damage in late winter and early summer, winter desiccation of needles, as well as damage to shoots and fine roots (Kullman 2005b). These changes may be more decisive for tree recovery and growth in northern Finland, where the frost-free season is quite short, varying between 50 and 100 days a year (**Paper II**). Furthermore, changes are also expected in disturbance regimes: an increased climatic stress results in increased fire regimes (Starfield and Chapin 1996), in increased frequency of climatic extremes (extremely cold periods, storms and eventually droughts), insect outbreaks and fungal diseases (Juntunen et al. 2002). At the timberline, in the peripheral parts of forests, these kinds of climatic disturbance are more significant for the survival or regeneration of vegetation.

5. SUMMARY AND CONCLUSIONS

The objective of the study was to investigate the influence of natural conditions on the small-scale spatial variation of climate in northern Finland, and to define the interaction and feedback mechanisms between the atmosphere and human activities, i.e., forest fires, and the vegetation in an ecosystem near the climatological limit of forests. In order to assess the impact of fires on the local climate, and in turn the effect of the changed local climate on the vegetation regeneration, the climatological and environmental conditions from a fire-disturbed site, the Tuntsa area in Salla, eastern Finland, have been analyzed and evaluated. The main findings of the study are as follows:

- The determining natural factors shaping the regional climate of Finnish Lapland are the geographical position, especially latitude, local topography and altitude. The effect of longitudinal location proved to be less significant, affecting principally the local features of precipitation distribution, but less that of temperature-derived quantities. The maritime influence was not significant, being limited to only the northernmost-situated areas. Unlike the southern and central parts of Finland, lakes have rather a local than a regional effect on climate in Lapland. This difference probably originates from the reduced amount of inland water bodies in northern Finland (**Paper I**).
- The Kriging interpolation method with a high (1 by 1 km) spatial resolution including the effects of ‘external forces’ proved to be an adequate method in the spatial representation of climatological variables (**Papers I** and **II**).
- The spatial distribution of air temperature-derived quantities had a latitudinal dependence, integrated with local features that are determined by topography and inland waters. Thermal conditions are mostly favourable in the southwestern part of Lapland, around the large lakes (Lake Inari and the Lokka- and Porttipahta reservoirs) and in the Kemijoki basin. The coldest regions are fell Lapland and the highlands (**Paper II**).
- The distribution of precipitation showed longitudinal dependence, but the influence of local features, such as rain-shadow and elevation, also appears (**Paper II**).
- The overall changes in the surface and environmental conditions due to the forest fire and continuous grazing activity resulted in significant changes in local climate, including heat and water fluxes, snow conditions and radiation processes (**Papers III** and **IV**).
- The removal of the original vegetation and its substitution by tundra vegetation resulted in an increase in wind velocity (60-65% stronger than in the forest) and in the probability of high wind speed (doubled). The altered surface roughness and wind climate caused vigorous snow drifting over the open, unforested area, resulting in a 30-50 cm thinner but compacted snow cover, having almost half the water equivalent and a shorter melting period compared to the snow cover in the spruce forest (**Papers III, IV**).
- The reduced snow accumulation and the lack of protection assured by the canopy and rich understorey resulted in a large seasonal variation of surface and soil temperature (18 °C in the upper layer) associated with deep soil frost (down to 0.5

m) and considerable variation in soil moisture content. The largest deviations in soil moisture were registered in the topsoil, which was more receptive to variations in precipitation during the warm season and variations in temperature in wintertime (**Paper IV**).

- The changes in evaporation and energy fluxes were a consequence of the structural parameters of the canopy, the variation of soil moisture and the solar radiation available for heat exchange. The amount of water evaporated from the forest constantly exceeded that from the tundra vegetation, and the partitioning of the dominant evaporation component differed over the two vegetation types. The amount and repartition of sensible and latent heat fluxes varied considerably (**Paper IV**).
- The altered surface and soil conditions, as well as the more extreme local climate conditions that evolved may have negatively affected the growth and survival of tree seedlings, ensuring unfavourable conditions for a successful reproduction of the original vegetation, and causing deviations in the regional position of the timberline (**Paper IV**).
- The current and the projected climate indicate favourable conditions for a northward progression of the timberline, although possible changes in the disturbance regimes and the local topoclimatic conditions may slow down and even completely prevent tree growth and the advance of timberline (**Papers II and IV**).

These negative feedback processes between the atmosphere-surface-vegetation emphasize the subarctic ecosystem's sensitivity to any disturbance. The objective of this study has been to study the climatological effects of human activities on high latitude vulnerable ecosystems. In order to understand the ecological aspects and processes that impede forest regeneration and determine stand dynamics in northern timberline habitats following human disturbances in the context of changing climate, further research is required. In providing detailed information and research results about climatological conditions and feedback in Finnish Lapland, this study may signpost a pathway for ecologists and forest researchers in the re-establishment of forest in disturbed northern areas.

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