

Sustainable development in northern timberline forests

Proceedings of the Timberline workshop, May 10–11, 1998 in Whitehorse, Canada

Sakari Kankaanpää, Tapani Tasanen and Marja-Liisa Sutinen (eds.)

The Finnish Forest Research Institute
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Foreword

Northern timberline forest workshop

A workshop on Sustainable Development in the Northern Timberline Forests was organised by Ministry of the Environment of Finland and the Finnish Forest Research Institute in Whitehorse Canada on 10-11 May 1998. This meeting was held to give the input by experts to promote international discussion about the development of common criteria for defining sustainable development in northern timberline forests, guiding it and measuring progress towards it. Altogether 56 experts from Canada, Denmark, Finland, Russian Federation, Sweden, United States of America, Finnish Sami Association, Gwich'in Renewable Resource Council, Indigenous Peoples' Secretariat, IUCN, RAIPON and WWF met in the Timberline Workshop.

The northern timberline forests were defined as a forest of circumpolar distribution where growth and reproduction are controlled by cold northern climate and/or higher elevation. Timberline forest joins the areas of continuous forest cover and tundra. These forests have a slow rate of recovery after disturbance and are often naturally fragmented.

The Workshop produced recommendations for common actions by the Arctic states concerning the definition of timberline forests, ecological criteria and indicators, threats and human impacts, protection, forest management, traditional knowledge and scientific research and reindeer and caribou. It was emphasised that sustainable management of timberline forest should be knowledge-based through collaborative research within the circumpolar zone.

The Workshop was very successful. The participants agreed that the timberline forest is an important vegetation zone for every circumpolar Arctic State. I would like to see that this good start would continue as international co-operation by the Arctic countries both in ecological and sustainable development perspectives.

The Timberline Workshop was held in conjunction with the Sustainable Development Conference in the Arctic (May 12-14, 1998), which was organised by Canada. Ministry of the Environment of Finland and the Finnish Forest Research Institute like to thank the Canadian

Forest Service and the Ministry of Indian Affairs and Northern Development for co-operation in organising the Timberline Workshop in Whitehorse.

Sauli Rouhinen
Environmental Counsellor
Ministry of Environment Finland

Workshop on sustainable development in the northern timberline forests

Whitehorse, Canada
10-11 May, 1998

Statement

Altogether 56 experts from Canada, Denmark, Finland, Russian Federation, Sweden, United States of America, Finnish Sami Association, Gwich'in Renewable Resource Council, Indegenous Peoples' Secretariat, IUCN, RAIPON and WWF met on 10-11 May, 1998, in Whitehorse, Canada, for a Workshop on Sustainable Development in the Northern Timberline Forests.

This meeting was held to give the input by experts to promote international discussion about the development of common criteria for defining sustainable development in northern timberline forests, guiding it and measuring progress towards it.

The participants,

- **note** that the northern timberline forests are a signigficant source of resourses in the Arctic. Although the utilization of timberline forests by the wood industry is still limited, many human activities occur in the zone or are dependent on it;

- **emphasize** the importance of the timberline forests as a circumpolar transition zone between the northern taiga (or boreal) and the tundra. The tree growth is restricted and often displays low regeneration capacity;

- **underline**, that although there exists considerable scientific information on this region in the Arctic countries, an ecological synthesis of the circumpolar northern taiga (or boreal) and the tundra transition zone is needed for future cooperation;

- **call** for the development of a definition of sustainable development in northern timberline forests and criteria for the measurement of progress toward achieving it by a cooperative effort among stakeholders, scientists, officials, experts, project planners, operators, user groups, indigenous and local communities.

The Workshop agreed on following statements and recommendations of working groups for common actions and cooperation by the Arctic States:

1. Definition of timberline forests; criteria and indicators for their sustainable management in the circumpolar region

Despite that the term "timberline" may appear confusing due to its use to refer to several different situations, we choose it because, nevertheless, it currently has the widest international understanding.

Timberline forests are:

Forests of circumpolar distribution where growth and reproduction are controlled by cold northern climate and/or high elevation. These forests have a slow rate of recovery of ecosystem structure and function after disturbance and are often naturally fragmented. Timberline forests join the areas of continuous forest cover and the tundra.

Because of differences in local conditions (species composition, history, anthropologic contexts etc.) between circumpolar countries, timberline forests can be managed with various strategies in order to meet sustainability criteria.

Because of their low regenerative capacity, these forests should be managed in minimizing the impact of exploitation (e.g. timber harvesting, subsistence activities, reindeer husbandry etc.). Sustainable management of timberline forests should be knowledge-based. Therefore we suggest the following areas of collaborative research within the circumpolar context: ecological mapping, sustainability monitoring and assessment, as well as the sociology and economics of forest ecosystem management.

2. Threats to and human impact on timberline forests, protection of timberline forests

The facts

The northern timberline forests are complex ecosystems consisting of diverse flora and fauna, containing significant natural and aesthetic resources. These areas are being subjected to an increasing number of threats, most resulting from human activities in Arctic and Subarctic areas. These include:

- Conflicting interests polarize groups of people, with public input that occurs on a range of subjects with which they have limited knowledge,
- There exist many unresolved conflicts that have harmed and continue to threaten the health of the timberline forests,
- In many regions, there is a bias towards commercial activities that generate income and jobs, over sustaining the timberline forests over the long-term,
- Factors such as expanding consumption patterns force resource extraction into the northern regions. The result is a focus on massive projects with regional impacts, such as oil development, hydroelectric, and large-scale mining,
- Increased access, technology, population migration, and market demands lead to increasing use of the timberline forests. These conditions lead to human activities that exceed the human carrying capacity in many areas,
- Human presence requires additional control over natural disturbances such as fire and flood, impeding naturally occurring processes,
- Even though many impacts affect large areas of the Arctic, decision making is splintered at local, regional, national, and circumpolar levels, with conflicting notions of who has control over the use of the resources,
- There are cultural conflicts affecting resource use, ownership, and management that lead to conflicting activities and potential for overuse,
- Some areas of timberline forests have been overgrazed and subjected to other unsustainable uses, severely affecting both human and natural ecosystems,
- Reforestation of areas with foreign species hurts the diversity of timberline forests ecosystems and could have irreversible effects,
- Global environmental changes are adversely affecting the timberline forests, including climate changes, cold deposition of atmospheric pollutants,

It is critical that we focus our efforts on managing people not resources. Humans are a critical part ot the ecosystem and need to be treated as such.

Research areas

Different regulatory standards and systems exist in different Arctic countries. These should be researched, with discussion about the potential for harmonizing systems.

Continue and expand research programs to understand the cumulative and interconnected effects of human activities that are incompatible with a diverse timberline forest ecosystem.

Develop a collected system of aggregating research on global level for consistently monitoring the timberline forests.

Research renewable resources, such as forests, berries, tourism, and alternative energy, to indentify viable economical and sustainable development activities.

Recommendations

- By managing human impacts, maintain the relatively intact ecosystem on a scale large enough to support growth and development of diverse and healthy wilderness and wildlife systems. The means to achieve this goal should include the development of protected areas as a result of multiple use area planning with a circumpolar focus. The sensitivity of ecosystems must determine the tolerable levels of impacts in any area.
- The human carrying capacity in any given area needs to be assessed and monitored.
- Set up systems of communication and education. Communication needs to be encouraged among governments to coordinate activities, and among people to share information. Educational programs should be developed so that individuals can understand the effects of their actions and the non-renewable nature of many elements of the landscape.
- The Guidelines for Environmental Impact Assessment in the Arctic should be implemented in all timberline forest areas, so that all impacts on a local, regional, and circumpolar basis are explored, relying on input from all people directly affected by the activity.

- Natural disturbances need to be factored into ecosystem management plans.
- The term "timberline forests" implies a product, sawn lumber, rather than a forest ecosystem. The name should reflect all aspects of the forest, such as "taiga/tundra" or perhaps Northern Transition Forest.

3. Forest management in timberline forests

Boreal timberline forests are more sensitive and less resistent than more southern or lower elevation forests.

The likelihood of response to global climate change must be incorporated in management decisions. Management should recognize importance of maintaining natural ecosystem characteristics and function. Natural levels of biodiversity are associated with the greatest positive resistance and stability.

Management should:

- be ecosystem-based, nature and biodiversity oriented
- be sustainable,
- include wide buffer against harsh climatic impacts and irreversible changes caused by man,
- be developed using community based planning with indigenous representation
- consider multiple forest resources and values, with the full range of stakeholders,
- be developed with landscape-scale planning (including zoning),
- place highest priority on personal and local use

Adaptive management that incorporates sound design will allow learning from past mistakes and taking advantage of soundly-based findings.

Monitoring of timberline forests and research of silvicultural methods should be done on an international and shared basis.

4. Traditional knowledge and community-based sustainable forest management

Definition: Traditional knowledge is the living knowledge about the land, wildlife and natural systems that has developed over generations. This knowledge has allowed indigenous people to live sustainably on the land, and has allowed the land to survive.

Mackenzie Valley as an example (the following text has been written by working group number 4):

"We recognize that in the past, forest - and of course many other renewable - resources have been utilized in a process that can best be described as 'southern driven'. This is clearly not sustainable. We believe that a pre-condition for sustainability in the northern transitional forests is the knowledge that northern peoples have. To reverse the process take our lead from many sources, such Brundtlad Report, UNCED - Rio, AEPS. We start, however, with a Cadanian product of the '70's, Justice Berger's Report, which recognized Homeland. First Principle - North is not a hinterland, it is someone's backyard. Northerness should set the goals and the limits of forest management, especially in such marginal areas as the northern transitional forests. The limits to sustainability have to be set locally. Second Principle - traditional knowledge must be applied to achieve these goals and limits.

We believe this should always be the model. However, realistically, in many places northern peoples are forced to react to old process. In such cases, appropriate Environmental Impact Assesment (EIA) practices must be employed where traditional knowledge can have an equal place in western science and engineering to counter innappropriates and unsustainable development plans. In the '70's, Justice Berger made several interesting points in his Mackenzie Valley report. First, not wilderness - it is Home. Unless it was treated like that, development in Canada's north should not proceed. Led to revitalization of Land Claims. Now, northern aboriginal communities have the power because they have a land base, legislative constitutional authority, financial resources - and therefore respect."

Other countries may find other ways but unless some way is found to bestow respect, traditional knowledge used to sustainably manage northern forests is unlikely to happen.

5. Reindeer and caribou in timberline forests

Facts:

- Reindeer and caribou require extensive areas compared to other deer and moose
-Timberline areas comprise important winter habitat for most reindeer/caribou populations, but for some populations these areas serve as year-round habitat as well
-Local people depend on reindeer and caribou for nutritional, cultural and economic reasons
-The overall condition of grazing lands is poor in many areas, such as northern Fennoscandia, Northwest Siberia and northern Quebec.
-Traditional migration routes are susceptible to new obstructions, such as hydropower reservoirs, pipelines, roads, etc.

Important to know:

- As animals alter vegetation/soils, what are the important implications - if any - for ecosystem functioning? For example, reindeer can be important in limiting the regeneration of favoured deciduous species near timberline, such as birch plantations in Lapland. They also affect succession on disturbed areas in Northwest Siberia.
- What are the traditional migration routes/grazing areas and how are these affected by regulations and/or physical obstructions (e.g. drilling in Arctic National Wildlife Refuge)?
- In areas with 'too many' reindeer, how to optimize pasture loads while balancing competing interests (e.g. 'state' versus 'private' herds)? For example, competition for grazing lands is likely to increase in Northwest Siberia as amount of terrain damaged by petroleum exploitation increases.

Recommendations:

- Take into account reindeer/caribou habitat (especially winter habitat) during land use planning (including all human use and forestry) in timberline forests.
- Monitor both animal population levels and pasture conditions
- Maintain reserve pastures in reindeer husbandry regions
- Regulate domestic populations (including introduced populations) to prevent unsustainable increases

6. Ongoing works

Helsinki and Montreal Process of criteria and indicators for sustainable forest management.
Concention on Biological Diversity
Discussions on an international forest convention.
Model Forests Programs
IUCN Boreal and Temperate Forests Programme (under development)
Northern Forum
Parliamentarians of the Arctic Region
Arctic Council
Nordic Council of Ministers
Barents Euro-Arctic Program
Agenda 21 (Forestry)
Montreal Protocol
National Forest Strategy
IPCC, Climate Change Convention and Kyoto Protocol
World Reindeer Herders Association
International Arctic Science Committee/ Project on reindeer/caribou grazing systems.

Compilation of timberline forests digital map and poster

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In support of WWF forest campaigning work, including *"Forests for Life"*, Global 200 and the Living Planet Campaign, Helsinki and Montreal Process of criteria and indicators for sustainable forest management.

Period of work: 3 months

Background: During the Workshop on Sustainable Development in the Northern Timberline Forests (10-11 May 1998, Whitehorse, Yukon) attended by 56 experts from 12 countries the northern timberline forests was defined as *a forest of circumpolar distribution where growth and reproduction are controlled by cold northern climate and/or high elevation.*

These forests have a slow rate of recovery of ecosystem structure and function after disturbance and are often naturally fragmented. Timberline forest joins the areas of continuous forest cover and tundra.

At the same time timberline forests are a significant source of resources in the Arctic and subarctic areas. Although the utilisation of timberline forest by the wood industry is still limited, many human activities occuring in the zone are dependent on it.

Although there exists considerable scientific data on status and specific consideration addressed to balanced development in different parts of this transitional zone in the Arctic countries, an ecological synthesis of the available information is needed for future international cooperation in field of sustainable development in northern timberline forest areas.

Development of a set of criteria for define and measure progress in sustainable development requires the clear definition of spatial

distribution of northern timberline forests, delineating of location of this area of special concern.

WCMC (World Conservation Monitoring Centre) will provide the poster map showing the circumpolar distribution of northern timberline forests and digital version supplemented with data on major climate and physical factors of major influence on ecological parameters of transitional forest-tundra ecosystems.

JUSTIFICATION: The draft map of circumpolar distribution of forest and forest types defined in different national systems presented to the participants of the Conference on Sustainable Development in the Arctic have attracted considerable interest. Experts considered that in addition to the education and promotion value of those kind of printed products it could be of high scientific and practical analytic value having available the digital version of the map of distribution of the forests of transitional zone.

WCMC experience with other global and regional datasets providing the basis for large scale integration of data on the distribution, status, protection of particular biomes and ecosystems indicates the possibility of request on the distribution of considerable amount of copies of printed and digital map of northern timberline forests.

It is proposed to make the digital dataset developed while the poster map preparation widely available for environmental institutions and NGOs via Internet and CD-ROM copies for users isolated from Internet facilities.

Implementation of the project involves cooperation of Arctic countries and UK (WCMC).

PRELIMINARY BUDGET

ACTIVITY	US$
Project supervision	1,800
Data gathering	3,200
Criteria and definition formalisation	1,200
Spatial Analysis, map generation	12,000
Printing, CD printing and distribution	10,000
TOTAL	28,200

The sustainability of development in northern Québec forests: Social opportunities and ecological challenges

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Introduction

Since Martin Frobisher's mining project in the 16th century, there have been at least five steps which represent the evolution of Canadian's perception of the North (Hamelin 1989):

a) An initial period of optimism associated with the promise of the Northwest Passage discovery, which proved erroneous;

b) the resulting view that the North was practically useless;

c) a more recent political perception of the North as an unlimited reservoir of natural resources;

d) a subsequent ideology of non-development illustrated by the slogan « Freeze the Arctic »;

e) a current objective of integrated planning that intends to respect all nordic cultures.

The held of this conference, and the origin of the participants, illustrate well the fact that this last perception is a growing concern

among circumpolar countries around the world. In connection with these concerns, I will present the northern Québec's perspective in an attempt to address the following objectives:

1) to illustrate the economic and strategic context in which sustainable development would likely take place in northern Quebec forests;
2) to provide the operational criteria on which the biogeographic divisions of northern Quebec are based, and finally;
3) to explore some of the ecological constraints to sustainability that exist in the forests of northern Québec.

The people

Ressource use sustainability has become a human value over the last few decades. In this respect, there are two basic ingredients that must first be considered when analysing sustainable development: people and the increasing demand for hydro-electricity.

The approximately 20 000 native people of the northern Québec-Labrador peninsula include the Inuit, Cree, Naskapis and Montagnais Nations (MRN 1996). The Cree are the most numerous. Their natality rate ranged between 40 and 50/1000 up to the 1970's (Croteau-Laflamme 1973) and they still maintain a high fecundity (Clarkson et al. 1992). They are geographically and culturally more inclined to use the available forest resources as more than half of the families still receive their main income from fishing, hunting and trapping. (Feit 1969; Weinstein 1976).

During the last 25 years, the construction of the Hydro-electric power plan over the in northern Québec has brought forth several profound changes, both in the landscape and the way of life of James Bay's aboriginal people. Construction began in the 1970's and involved thousands of workers; this in itself constitute a stressful situation for native people not used to such industrial activity. The flooding had an immediate dramatic impact along the La Grande River, originally one of the most productive and diversified forest habitats in the region. The forest that was cleared prior to the flooding consisted of « tall timber » for the region, which emphases this habitat's quality. The massive removal of the entire forest along this valley induced a landslide process that was generalised along the river. Up to 11 000 km^2 of taiga was flooded to form 4 reservoirs, namely the Robert-Bourassa, LG3, LG4 and Caniapiscau Reservoirs. (Carte de distribution des communautés autochtones). The hydrographic network of approximately 20% of the northern Québec area was modified through this hydroelectric complex. The flooded area encompasses traditional trapping and hunting territories

of several native families, seasonal meeting grounds, sepultures and other aboriginal sacred sites.

The LaGrande Hydro-electric Power Plan involved a long process of negotiation between First Nation (Cree and Inuits) representatives, the Canadian Government and authorities from the province of Québec. These on-going discussions resulted in The James Bay and Northern Québec Agreement that was signed on November 11th, 1975 (SDBJ 1991). This landmark document aimed to promote the First Nations' traditional lifestyle while providing them with the necessary tools for their social and cultural progress, as they view it, such as local health and education services, etc. Further, this document set the stage for both the development and valuation of the North's natural resources (e.g. energy, well in northern Québec.

For better or worse, the LaGrande Hydro-electric Project induced a sudden burst of jobs, almost exclusively for thousands of non-native southerners. The arrival of thousands of new people dramatically increased the demand on wildlife resources.

Further, for the Cree population of northern Québec, the improved health and educational services along with an improved economy contributed to increases in both number and needs. Altogether, these factors increased the pressure on northern forests for subsistence, recreation, and business activities.

Biogeographical settings

What are these northern forests? The northern boreal, or taiga, and forest-tundra zones make up 47% of the Québec-Labrador peninsula area (Richard 1988). They are mainly distributed between latitudes as low as the 50th up to the 57th parallel. Two main climatic gradients influence the vegetation. There is a northward decrease in the heat sum available for growth as well as a parallel decrease in the total precipitation.

The forests of this region have a recent postglacial history similar to its western American counterpart (Ritchie 1987). The chronology of Laurentian ice melting suggests that the postglacial migration of tree species was done along two routes, the Labradorean and the Hudsonian (Payette 1993), and in the central Québec-Labrador peninsula, it was not completed before 5000 BP. This is therefore a relatively young forest landscape, as are most circumpolar boreal and subarctic landscapes.

In the Québec-Labrador peninsula, the zonation of the northern forest vegetation has a marked latitudinal component which primarily reflects the influence of major climatic gradients. The terminology and criteria currently in use are the following:

The boreal forest proper has a continuous forest cover, mainly dominated by balsam fir with companion deciduous tree species in the southern part, and by black spruce in the continental north. The forest floor in this area is covered by mosses. The latter zones are intensively managed by the forest industry under a sustained supply regime.

North of the black spruce-feather moss zone is the call taiga, a lichen woodland which is still within the continuous boreal forest (*sensu* Hustich) while the density of tree populations can be low. The taiga is subjected to increasing logging pressure despite severe restrictions set by the Quebec department of forest, as it is considered a low regeneration capacity forest type (Gouvernement du Québec 1987).

The taiga zone ends with the northern limit of the continuous boreal forest. North of this limit, the forest landcape opens quite abruptly (Timoney *et al* 1993) to form the forest-tundra, a 350 km wide zone subdivided into the forest sub-zone where the tree growth forms are predominantly arborescent and in the shrub subzone where tree species exist only as krummholz. This conception of the forest-tundra avoids the confusion created among ecologists who used the term « treeline » to refer to landscapes where the forest cover and the lichen-heath cover intermingle. Schematically, the zonation of the northern vegetation east of Hudson Bay is characterised by the northern boreal forest that ends at the northern limit of continuous forest as lichen-woodland, then the forest-tundra where the forest only partially covers the potiential sites. The treeline corresponds to the northernmost area reached by trees in arborescent growth form (that is > 5 m; Payette 1983).

Are northern Québec forests a naturally sustained ecosystem?

Now that forest zonation has been portrayed, a basic starting point to analyse the question of sustainable development in northern forests is understanding both past and recent natural dynamics of the system. One of the most important driving factors of northern forests is fire. Tens or hundreds of natural fires burn each year in the boreal forest and forest tundra of Québec; the situation is worse north of 52° N since most are not fought at such high latitudes. The modern fire rotation period in the northern boreal forest is 100 yrs; it increases to 180 yrs in the forest sub-

zone of the forest tundra, and to nearly 1500 yrs in the shrub sub-zone (Payette *et al.* 1989). The first occurrence of paleofire in northern forests (Desponts & Payette 1993; Filion 1984) suggests that fires were active in this period, and may have completed several tens of cycles during the late Holocene period.

The presence of coniferous charcoal below the humus layer in most sites of the forest-tundra currently devoid of trees, clearly suggests that in this area, the forest cover was greater in the past (Payette & Gagnon 1985). In the Québec-Labrador peninsula, this is also supported by palynological data which show a higher input of black spruce pollen in sediments 3000 to 5000 yr B.P. (Lamb 1985; Richard 1979, 1995; Richard *et al.* 1982). There is a converging set of evidence suggesting that the forest-tundra is the end-product of a fire-induced deforestation process.

The forest resilience along a boreal-treeline transect

It seems that northern forests have not constituted a self-sustained system in the past. What are the likely mechanisms involved in this landscape-scale process? We have tried to measure the forest resiliency to fire with postfire regeneration surveys (Sirois & Payette 1991). Because the postfire recruitment of black spruce and Jack pine typically peak some year following the fire and become sporadic afterward (Morneau & Payette 1989; DesRochers & Gagnon 1997), the quantity of seedlings established soon after a fire is a conservative estimate of the quantity of trees in an even-aged mature forest. Further, because only the fine fuel is consumed during a fire and tree trunks require many decades to decompose, we can then compare the forest structure as it was immediately before the fire and regenerated since all in one step. In order to evaluate the forest resiliency to fire along a South to North gradient, regeneration surveys were done on the large 50's fires that burned across the boreal and subarctic areas of Québec. At each of 200 points, a comparison of the pre- and post-fire tree population density was made into a forest resiliency index. The results indicate that 93% of the upland sites of the shrub sub-zone experienced a 75% minimum decrease of their original density whereas the majority of the northern boreal, well drained sites experienced a noticeable density increase (Sirois & Payette 1991). Overall, these results support a northward decrease in the post-fire regenerative capacity of forests. Notice that up to 20% of the northern boreal sites regenerate poorly, if at all. A similar trend was observed in the northern boreal forest east of James Bay in the 1989 fire. In the 23 000 km^2 of wilderness that was burned during this year, the regeneration

survey indicates that most sites are currently experiencing severe deforestation (Lavoie & Sirois 1998). Overall, these regeneration surveys suggest that there is a strong potential for the southward expansion of the forest tundra, at the expense of the northern boreal forest.

Sustainability and climate change

Because the notion of sustainability involves a long-term vision, we must anticipate the new conditions that may be caused by climatic change. While an increased growth rate may result from a warmer climate, the effects of climate change on both fire regime and the tree's regenerative capacity may have profound impacts on forest composition and distribution in northern Québec.

For a thorough review of factors associated with changes in fire regimes see Weber & Flannigan (1997). In the more specific context of James Bay's forests, there is some evidence suggesting that species which are poorly adapted to post-fire regeneration such as balsam fir and white spruce (Sims et al. 1990) might expand in the area if a moister, less fire-prone climatic period occurs. For example, at its northern range limit in James Bay balsam fir populations had markedly increased their density within old-growth spruce-fir forests during the snowier 20th century. A low fire frequency would also favor the expansion of white spruce at the treeline (Payette & Filion 1984).

In contrast, a climatically-driven increase in fire frequency would result in shorter fire intervals, and in a higher risk of deforestation in young stands with low regenerative capacities.

Balsam fir expansion, and increased deforestation rates of deforestation represent extreme, yet plausible, scenarios for opposing trends. In-between, however, the fire-climate interaction could have interesting effects for sustainability in northern forests. This aspect has been studied with FOREST-TUNDRA, a simulation model that takes demographic processes, the temperature control on growth and seed production, and the lichen mat control on seedling establishment into account (Sirois et al. 1994). Results suggest that the effect of a warming climate on forest density and productivity would be more pronounced if there are recurrent fires than if a forest faces only a warming climate. Therefore, the open forests of the taiga and forest-tundra offer the highest potential for increased productivity in response to fire-climate interaction. In the taïga and forest-tundra, the very low tree density on vast expenses of land without edaphic limitation likely originates from a

postfire regeneration problem rather than from any climatic limitation to growth. It can be suggested that most of the northern forests' responses to climate warming will be mediated by the tree species' reproductive processes as well as their controls.

Testing Hustich's hypothesis in northern Québec forests

Hustich (1966) was the first to suggest that the northern vegetation zones were associated with the south to north decrease in the regenerative capacity of forests. In order to test this major hypothesis in northern Québec, reproductive parameters were monitored on 156 trees, distributed in four sites: Broadback river, Radisson, Kuujjuarapik-Whapmagoostui (K-W) and Boniface river. This is a 750 km transect, from the southern taiga to the treeline. From South to North, the average difference in heat sum is 650 degree-days > 5°C. From 1989 to 1995, the cone and seed number, the sound seed percentage and their germination power were evaluated on the same trees.

From year to year, the median cone crop was generally < 50 with some bigger crops in the K-W site in 1991, 1992 and 1994. The cone number produced by most trees at the forest limits do not generally differ from most southern sites. In most cases, at the treeline, trees invest a significant part of their carbohydrate intake in reproductive structures.

Generally, the total seed crop does not differ between each of the 3 forested zone sites, however it markedly decreases at the treeline. Most of the time, cones from the northern treeline did not open.

The filled seed percentage displays the anticipated South to North decrease in regenerative potential as predicted by the Hustich Hypothesis. This percentage is generally above 50% in the two stands of boreal forests while it decreases between 40% and 0% in the forest-tundra, particularly at the forest limit.

The germinating power discussed here only represents that of filled seeds. Germination in the northern boreal forests frequently reach up to 80 % in the Broadback and the Radisson areas, but it generally ranges form 0 to 40 % in the forest-tundra. Seeds from the treeline have a germinating power which is generally close to nil. The geographical pattern of seed germination is about the same as the proportion of filled seeds with both factors decreasing with increasing latitude. Regression

analysis confirms a weak relationship between the heat-sum of the preceding year and the cone and seed crops. However, there is a tight and highly significant relationship between the percentage of filled seeds and their germinating power.

Overall, these results clearly show the South to North decrease in the trees' regenerative capacity which is close to nil at the treeline. However, even at the treeline, there are a significant amount of cones produced. The prevailing climate is more limiting to the final phases of seed production. Because reproductive structures appear to develop readily up to the treeline, a moderate and sustained warming may have profound effects on the regenerative capacity of northern forest, and this may be conducive to the increase in the tree density in the open lichen woodlands.

Challenges and opportunities of sustained development in Québec's northern forests

After this overview of the norhtern Québec case, what conclusions can be draw as challenges and opportunities associated with sustained development in northern forests?

At first, the challenges may appear as opportunities and vice versa. The first priority opportunity (or challenge) must consider the people that inhabit the northern forests above all. In northen Québec, the traditional uses of forest resources by a small population of native people must not only be preserved, but must also continue to be encouraged among the young. When done within the limit of resource sustainability, the pursuit of these activities has a strong cohesive effect on this social group.

Recent uses of forest resources, primarily by non-native people, has induced a new set of ecological forces on northern ecosystems. Some new villages have been created, others have become more populous still others have disappeared. These newly created social conditions in a quasi virgin forest environment, constitutes in itself an opportunity to experiment sustained ways of life instead of the usual wilderness depauperisation that generally follows human colonisation (Martin & Klein 1984).

Further, most pristine forests of the world are located in northern boreal and subarctic areas (Bryant *et al.* 1997). In the context of a global biodiversity impoverishment, these northern forests constitute a world

heritage. International sustainability standards must be developed in order to offer both the land use planners and the forestry business opportunities to play important role at the global scale through their decisions regarding the management of these forest environments.

We are however constrained from reaching these goals by several difficulties, each representing a challenge:

In forest exploitation, which must be restricted in the taiga zone already described, special attention must be paid to develop sylvical procedures that preserve the wilderness diversity at the regional level. Technical progress is growing rapidely in this field and must be accentuated in northern forests as they produce a substantial part of the diet for many native families.

Another type of challenge is concerned with the transient state of northern forests. It has been suggested that one of the most efficient ways to detect trends in both northern vegetation dynamics and distribution is to examine the post-disturbance responses of forests. The present meeting provides the best opportunity for launching the idea of a circumpolar monitoring network of northern forests' postdisturbance responses.

Finally, the accelerated rate of human origin changes in northern forests constitute an experiment at the global scale. As children, we have learned to include controls in our experiments. Any effort to promote sustainable development in northern forests must be paralleled by an effort to preserve a control of large areas of northern forest wilderness.

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The northern timberline in relation to climate

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Introduction

The timberline is a labile combat zone, a "Kampfgürtel" or "Kampfzone", where the protective forest encounters an open windy landscape, and it is often used as an indication of a boundary, a discontinuity, between extreme, harsh conditions and more moderate ones. It is a conspicuous phenomenon in the visible landscape, either abrupt or gradual. It is a very traditional, still fascinating, phyto-geographical complex of problems, one of which is its climatic characterization. Proposals have appeared in the scientific literature for more than a hundred years concerning the climatic indicators that best denote the location of the timberline, but there are still difficulties in delineating it, concerning, for example, the indefiniteness of the concept of timberline, its highly variable nature both physiognomically and taxonomically, and the sparseness of representative climatological records for timberline environments. Some authors stress the ecological diversity of the timberline, while others consider it to be ecologically almost equivalent world wide.

Timberline terminology

The terminology referring to the timberline belt, i.e. the transition between continuous forest and treeless terrain, is ambiguous, and a number of concepts are needed. The timberline terminology suggested by Hustich (1966, 1979) is well-known and appreciated (Fig. 1; see also e.g. Atkinson 1981, Payette 1983).

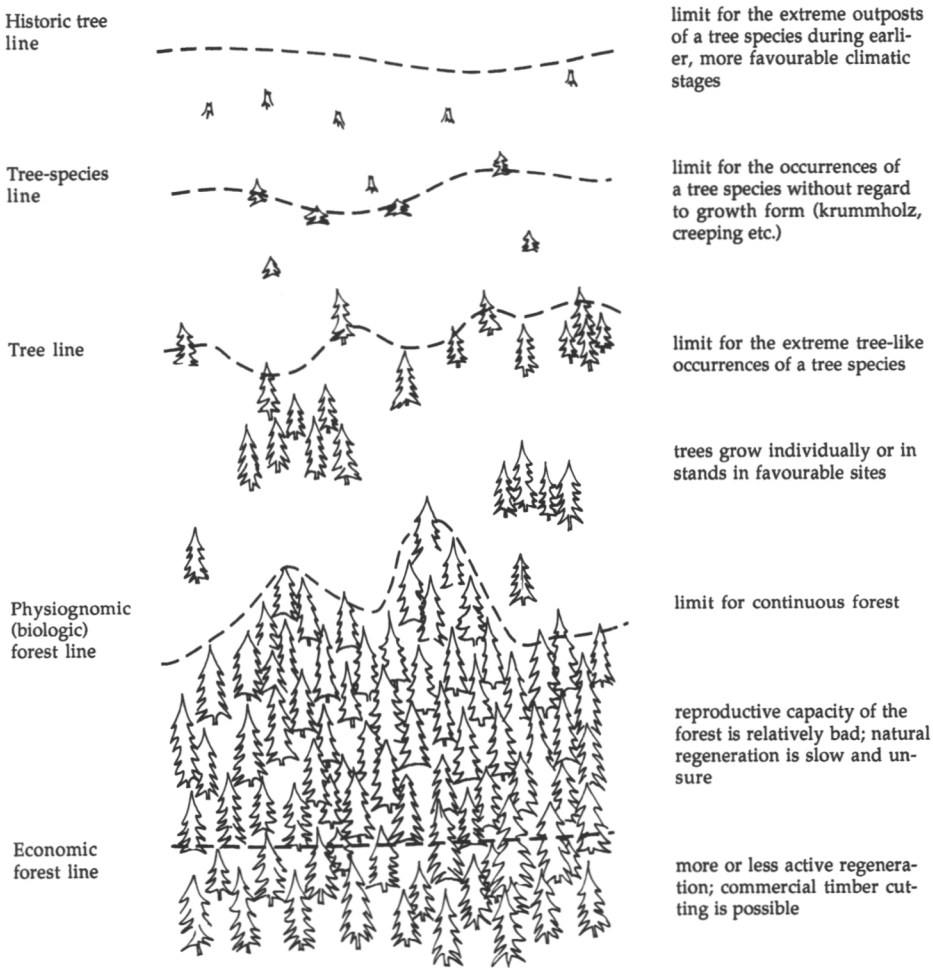

Fig. 1. Different tree and forest lines, according to Hustich (1966), modified after Tuhkanen (1982) and Heikkinen (1984).

The economic forest line constitutes the boundary for secure timber exploitation. Up to this line, forest regeneration is active and continuous on an annual or nearly annual basis. The line is difficult to locate precisely, because the limit of annual regeneration shifts in response to fluctuating weather conditions. The second limit is the physiognomic (also called phytosociological, empirical, biological, or vegetative) forest line, the limit of continuous or almost continuous forest cover. At this line forest regeneration is slow and unsure, and seed years are rare (Mikola 1978, Pohtila 1980).

Isolated trees and small stands of trees, even forest patches, characterize the area between the physiognomic forest line and the treeline proper, which is the extreme limit at which trees still achieve arboreal form and size (Fig. 2). Eventually the tree species limit is reached. This represents the furtherst outpost of one or more tree species without regard to growth form. This line is probably the easiest limit to locate on a map and the one that allows the least margin for interpretation.

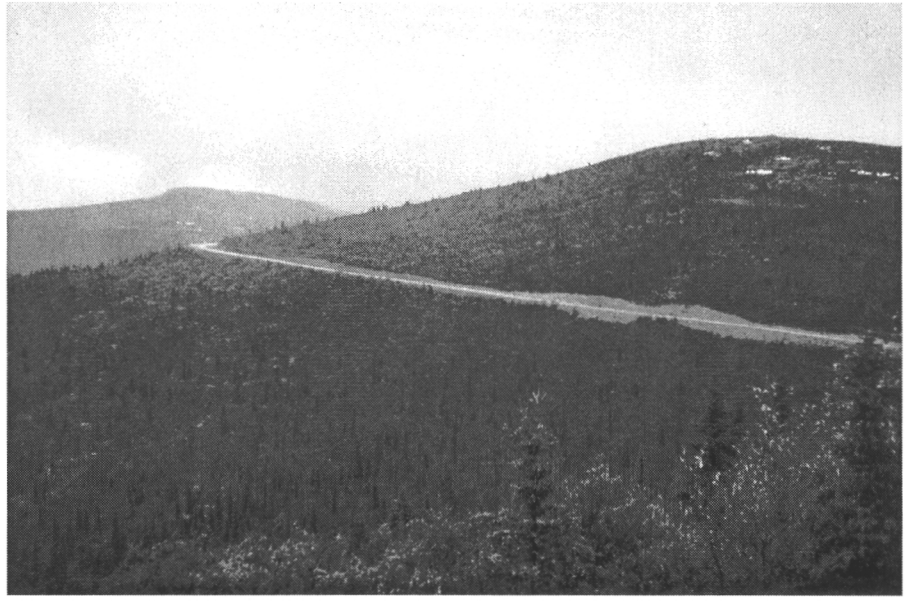

Fig. 2. The timberline zone formed by Picea glauca, the white spruce, in the inner parts of Alaska close to the Yukon boundary. The continuous forest rises highest in the sheltered furrows. The trees become more and more sparsely spaced and finally they grow only as badly deformed bushes. (Photograph: Sakari Tuhkanen)

The term "timberline" has been variously used. It may refer to the economic forest line or even to the treeline proper. I will use it here in a general sense to refer to the transition from forests to treeless vegetation (cf. Wardle 1998). The timberline belt is thus an ecotone between two habitats. The term timberline forest will have a central role in this workshop and the subsequent conference but there is no unanimous definition of it (cf. Kankaanpää & Vormisto 1998). In general terms, I would consider it to refer to forests and forest patches between the tree line proper and the economic forest line. Again, there are difficulties in defining the economic forest line, and it may have to be taken as a line

south of which natural reproduction of the forest is assured under prevailing climatic conditions.

Two important reports on timberline forests and their management, especially in Fennoscandia, have been published recently: Veijola (1998) and Tasanen (1998). Tasanen et al. (1994) is a comprehensive report on the timberline as a target of research (but only in Finnish), and includes a valuable bibliography.

The timberline region, with its tree and forest limits occurring in accordance with the environmental gradient, is a zone where the trees are struggling for existence by trying to adapt their means of regeneration, growth forms, statures and physiological and genetic properties to the extreme circumstances. The width of this compact zone may vary from some tens of metres in the mountains to tens or hundreds of kilometres in polar areas.

It has been suggested that under natural conditions, the timberline would be sharper than a transitional belt from the forest line to treeless vegetation. In some cases, that is true. In the southern beech forests (Nothofagus Blume) of New Zealand or southern South America, for example, the forest line and treeline often coincide (Wardle 1974), but in many mountain areas and at northern latitudes, the natural timberline belt is an ecotone of varying width that extends from closed forest to isolated dwarfed scrub-like trees, or krummholz (Holtmeier 1985a).

Different opinions have also been put forward on what constitutes a tree (Eidem 1955, Hustich 1979). The word is generally understood to mean a plant of a certain size with a woody stem that is "tree-like" in shape, and obviously not a shrub. Braathe (1977) sets the minimum height for a tree is at 3 metres at the forest line and 2.5 metres at the treeline proper.

When working on a large scale, it makes little difference whether a tree is considered to be the height of a man, 2, 2.5, 3, or perhaps 5 metres, but problems may arise from the requirement of "arboreal form and size". In some papers, for instance, the mountain birch (Betula pubescens Ehrh. subsp. czerepanovii (Orlova) Hämet-Ahti, also known as subsp. tortuosa (Ledeb.) Nyman) in northern Fennoscandia is not included as a resident of the forest and treelines. Mountain birches can be relatively tall and arboreal, but often they are low-growing (although exceeding 2 or 3 metres) and bush-like, with multiple stems. The mountain birch forests of northern Fennoscandia, occurring beyond and above the coniferous forests, should be included in the boreal zone proper (Ahti et al. 1968, Haapasaari 1988: 35), and not in the forest tundra (≈ hemiarctic subzone), as is sometimes done.

I will not go into detail on zonational terminology (forest tundra, scrub tundra, subarctic, etc.), because there are almost as many definitions and landscape subdivisions as there have been ecologists working with the timberline ecotone, and traditions differ from one country to another (cf. Fig. 3). The term 'subarctic', in particular, has a very variable and vague meaning (cf. Fig. 4; see also Ahti 1980). However, in order to be able to correlate local ecological work in various parts of the circumpolar regions, a more widely used and generally accepted nomenclature of ecologically pertinent concepts is desirable (Hustich 1979). This concerns not only phytogeography and plant ecology, but also zoological, palaeoecological and other research.

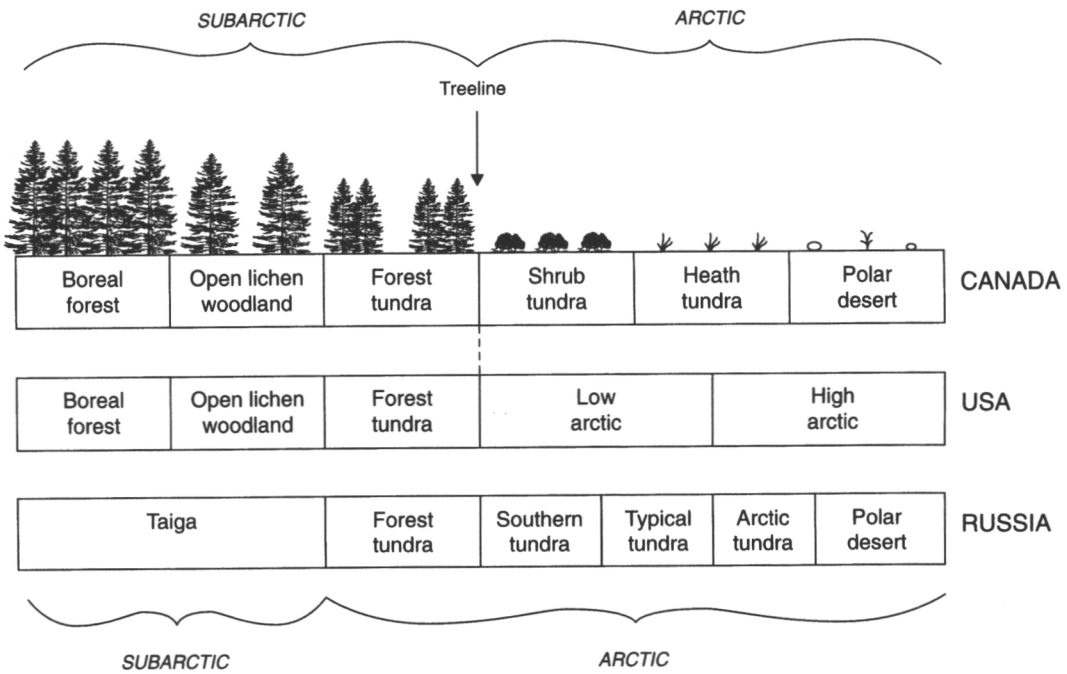

Fig. 3. Examples of definitions of ecozones on both sides of the northern timberline according to US, Canadian and Russian usage. (Briggs et al. 1997: fig. 24.3)

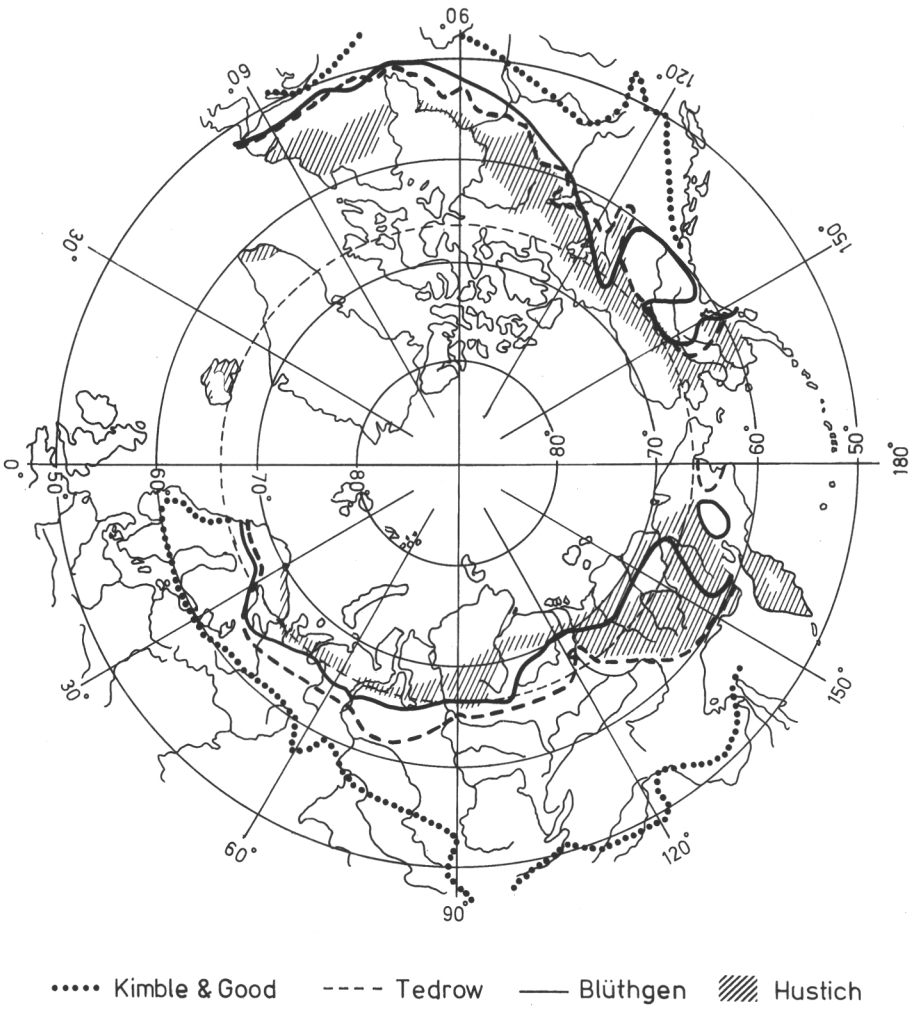

Fig. 4. Delimitation of the subarctic zone according to various authors. Differences may be of the order of one thousand kilometres. (Kimble & Good 1955: fig. 1; Blüthgen 1970: fig. 10; Tedrow 1970: fig. 2; Hustich 1972: fig. 2)

Certain attributes are commonly attached to tree and forest lines. In many cases there is evidence that ancient trees grew north of the treeline that is apparent today. Palaeobotanical investigations have shown that the position and species composition of the timberline are regulated by climatic fluctuations and the propagation history of the tree species in postglacial times, and locally by many other factors, as discussed above (e.g. Eronen & Huttunen 1987, Hyvärinen 1993, Seppä 1995). Hence, a definition of present and historic may be needed. The historic treeline is frequently considered to be the highest postglacial treeline.

Timberlines are often delineated as potential or actual. Potential implies that the limits that are controlled mainly by climatic conditions and possibly other natural environmental factors such as topographic and edaphic conditions. In reality, however, human activity has forced the timberline to retreat extensively. The lines presently encountered are considered actual timberlines. Potential is often natural, but not always, and natural is not always potential. It is possible, for instance, that the trees and forest have simply not had time to return to the Alaskan Peninsula and the Aleutians after the last glaciation. The Faeroes and the Falklands are naturally treeless, but there is no doubt that they were not within the potential timberline. The terms natural and anthropogenic may also be useful.

Latitudinal and altitudinal timberlines correspond to horizontal and vertical lines. The vertical and horizontal timberlines coincide at high latitudes. Polar timberlines are encountered in the Northern and Southern Hemispheres, and hence the attributes Arctic and Antarctic are used. This may be misleading, for the treeline towards treeless regions in the north or south can hardly be taken as a definite criterion for the limits of the Arctic and Antarctic phytogeographical zones. There are some regions, oceanic regions in particular, that should be included in the boreal phytogeographical zone (or antiboreal, austral or cool temperate in the Southern Hemisphere), but they are treeless. Simply northern and southern timberline would be more neutral terms in a global connection.

As far as the altitudinal limit of forests is concerned, the concept of an upper or lower timberline is relevant. The upper timberline is often called the alpine timberline, but the word upper is more applicable in a worldwide sense (Troll 1973), without any reference to the Alps. There may also be a lower timberline in the mountains, resulting from decreasing rainfall, cold-air drainage, or anthropogenic factors.

There is a difference in the character of the timberline between pronounced oceanic and continental regions. If the climate is highly oceanic, as in western Norway, for example, the polar timberline, especially that of coniferous forests, turns southwards and may be characterized by the term oceanic or maritime timberline. A phenomenon parallel to the oceanic and continental trends of the latitudinal timberline is the increase in altitude of the upper timberline from the coast inland in coastal mountain ranges. The increase in the altitude of the timberline from the edges of a mountain range towards its inner parts is known as the "Massenerhebung effect", that is, the influence of the size of a mountain massif on the elevation of the upper timberline (Brockmann-Jerosch 1919, Fægri 1971, Arno & Hammerly 1984).

The northern timberline

The northernmost point of the northern treeline (in the strict sense) in the Northern Hemisphere (Fig. 5) is located on the Taimyr Peninsula, at latitude 72°40' N. (Tikhomirov 1970), but its southernmost points are a matter of interpretation. Areas on the coast of Newfoundland are treeless at 48° N., and the treeless Aleutian Islands reach 52° N.

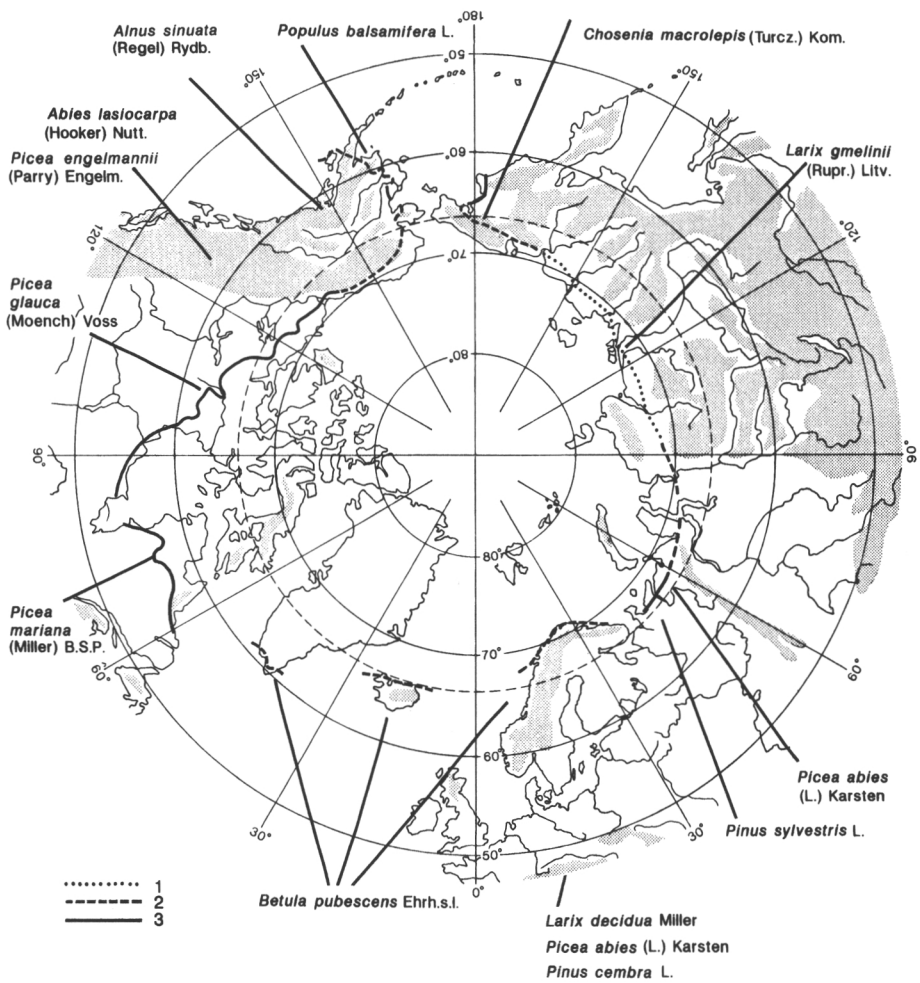

Fig. 5. The northern timberline: (1) Larix, (2) deciduous broad-leaved trees, (3) evergreen conifers. (Tuhkanen 1982, modified)

The timberline in general is a heterogeneous boundary in both an ecological and a taxonomic sense, and thus different tree species

constitute the polar and alpine timberlines in different parts of the world (Hermes 1955, Hustich 1966, Troll 1973, Wardle 1974). This is also the case with the northern timberline.

The northern timberline is formed by evergreen and deciduous conifers, especially in continental areas, and usually by broad-leaved species in oceanic areas. Evergreen broad-leaved species do not form the northern timberline, and they are extremely rare as timberline species elsewhere in the Northern Hemisphere outside the tropics (Wardle 1974, Ohsawa 1990).

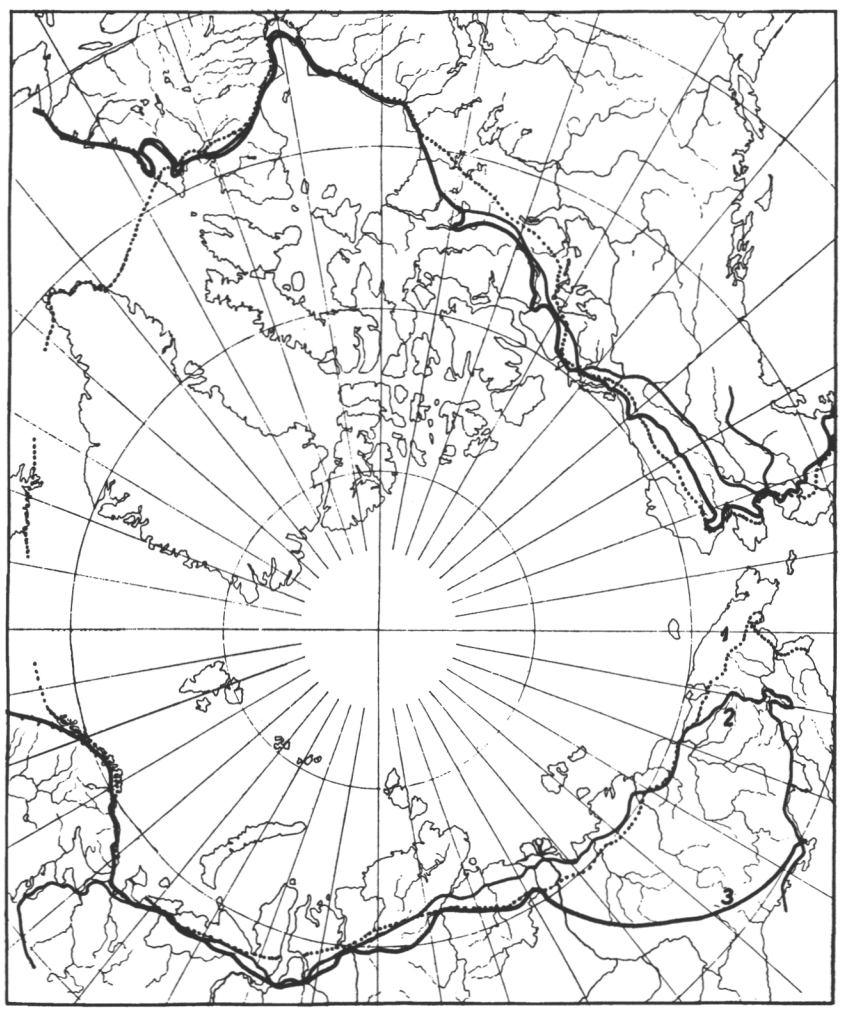

Fig. 6. A comparison of (1) northern treelines of broadleaved trees (formed by tree-sized Betula L., Populus L., and Chosenia Nakai), (2) the northern treeline of Larix Miller, and (3) evergreen conifers (except Pinus pumila (Pall.) Regel) and Juniperus L. spp. (Hustich 1966).

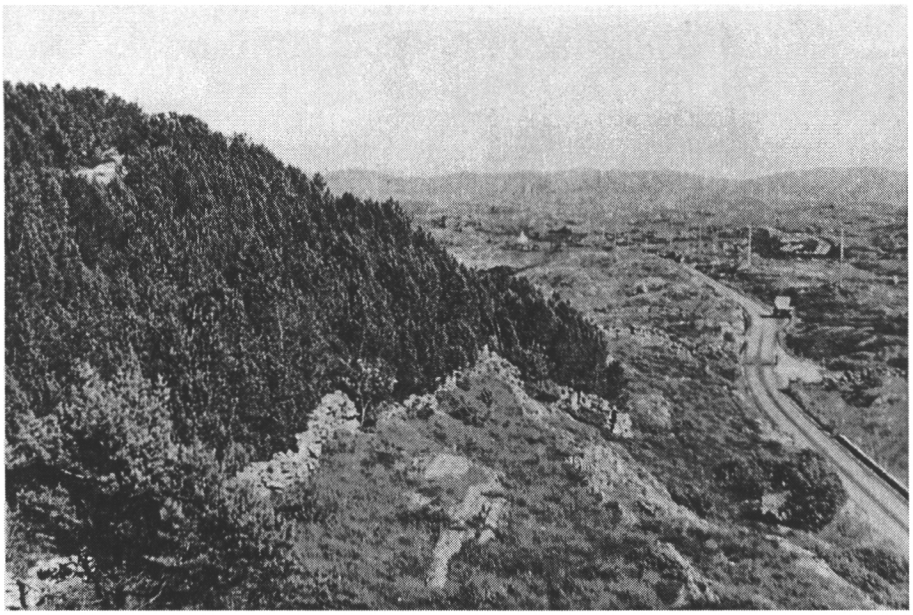

Fig. 7. A view of the island of Sotra, located close to Bergen on the western coast of Norway. The island is almost treeless, but the contorta pine (Pinus contorta), a western American species, grows well within the inclosure. It is obvious that grazing has expanded the treeless zone along the western and northwestern coasts of Norway, but there would probably be treeless patches on the windiest sites, at least, even without anthropogenic factors. (Photograph: Sakari Tuhkanen)

If we distinguish between timberlines formed by broad-leaved species, the larch (Larix Miller) and evergreen conifers, the limits almost coincide in the central parts of the continents and diverge most obviously in the extreme east and west of both Eurasia and North America (Fig. 6).

In western Norway the timberline turns south. The treeless heaths of this area are probably climatically conditioned, although they have been extended considerably by human activity (Lindemann 1970; Fig. 7).

The Faeroe Islands have been treeless throughout post-glacial time, but planting experiments have shown that they lie well within the potential timberline (Ødum 1979, Tuhkanen 1987; Fig. 8). Iceland once had extensive birch forests, which were mostly destroyed by human activity (Grøntved 1942, Blöndal 1987). Even under natural conditions, however, birch would probably avoid the most oceanic parts of southwestern Iceland (Grøntved 1942). The field-layer and ground-layer flora points clearly to the northern half of the boreal zone, bearing a

resemblance to that of northwestern and northern Norway, but there is, however, a marked Arctic element which is largely attributed to the highly oceanic climate and the dispersion history of the plants (Jónsson 1905, McVean 1955, Steindórsson 1962). In spite of the superficially tundra-like physiognomy of the Icelandic vegetation, the inclusion of Iceland in the Arctic zone, except at higher elevations, cannot be justified.



Fig. 8. A tree plantation from the beginning of this century is nowadays a popular park in the centre of the town of Thorshavn on the Faeroes. It is a very green, lush oasis with a great number of tree and bush species. A considerable part of the area was destroyed in a severe storm a few years ago. (Photograph: Sakari Tuhkanen)

Southwest Greenland has a small area in the northern boreal zone. Local climatic differences are great in this region, with its highly oceanic, windswept coasts and its sheltered inland valleys in which some relatively continental spots can be found. Areas that lie within the potential timberline for conifers are limited. Apart from the natural birch forest, some of the treeless heaths also belong to the northern boreal zone (Böcher 1979).

On the eastern coast of Labrador and Newfoundland, the timberline, especially that formed by coniferous species, turns sharply southwards. The effect of cold ocean currents is clearly reflected in the climate. The growing season is cool, damp and windy, and the winters are much

colder than on the western coasts. The coastal heaths resemble those in northwest Europe (Meades 1983). At lower altitudes, especially in Newfoundland, these heaths are mostly anthropogenic in origin (Ahti 1959).

On both sides of the Bering Sea the timberline turns southwards when approaching the coastal areas. There it is possible to delimit an amphi-Bering heath formation, corresponding to the amphi-Atlantic one, and comprising the greater part of the area of the Kurile Islands, part of eastern Kamchatka, the Aleutians and southwest Alaska (Lavrenko 1950). The treeless nature of some of these areas may be attributed to historical factors or anthropogenic causes. The treeless Aleutian Islands and southwest Alaska are often classified as Arctic or "oceanic tundra" (Hustich 1966, Young 1971). The dominant plant communities close to sea level, however, are not characterized by Arctic species (Tatewaki 1958, Hämet-Ahti 1979a), and the area can very well be included in the northern boreal zone (Hämet-Ahti 1979a, 1981, Tuhkanen 1984).

In the opinion of Griggs (1934), the forest has simply not had time to return to the Aleutian Islands since the last glaciation, and the timberline has certainly been shown to have advanced westwards on Kodiak Island during this century (Beals 1966, Bruce & Court 1945). Planting experiments have been successfully carried out with Sitka spruce (Picea sitchensis) at Unalaska Bay, for instance, and the trees have regenerated naturally (Alden & Bruce 1989).

Accordingly, there are about ten noteworthy tree species forming the northern polar timberline. In relation to the number of tree species in the world, or even in the boreal forest zone, this is of course a small number. Taxonomically, the trees forming the timberline are different on the two sides of the Atlantic, although the habitats of the northern tree species and their reaction to external factors are very similar. This fact led Ilmari Hustich to contemplate: "Is the Atlantic Ocean or the Bering Strait a bigger barrier for the ambitious taxonomist than the biological reality itself motivates?" (Hustich 1983).

The southern timberline

For the sake of comparison, let us take a short look at the southern timberline.

The southernmost point of the treeline in the Southern Hemisphere (Fig. 9), in the Cape Horn Archipelago, is at latitude 56° S., and the northernmost point is between Île Amsterdam and Île St. Paul, at latitude

38°30' S. The general thermal level of the extra-tropical Southern Hemisphere is lower than that of the Northern Hemisphere, because of the Antarctic ice (Weischet 1978). The southern timberline is oceanic throughout, the degree of oceanity being generally higher than anywhere on the northern timberline. In both hemispheres, the difference between the northernmost and southernmost points of the treeline is about 20 degrees of latitude.

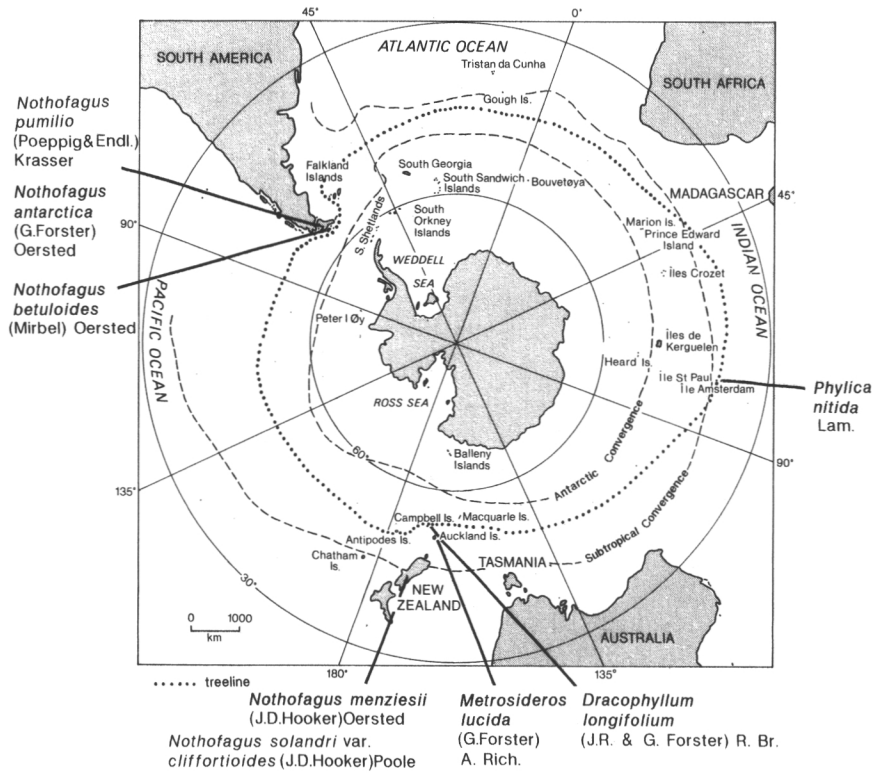

Fig. 9. The southern treeline (Brockmann-Jerosch 1928, Troll 1978, modified).

The climate of the south Chilean archipelago is very humid and windy, and soil drainage is poor. Moorland formation dominates, but patches of forest occur at protected sites even on the outermost islands (Young 1972, Dollenz 1980, Pisano & Venegas 1984). The physiognomy of the moorland formation may superficially resemble that of tundra or forest tundra ("tundra magallánica" or "Magellanic tundra"), but such a name is hardly appropriate from an ecoclimatic or phytogeographical point of view.

There is no real latitudinal timberline on Tierra del Fuego, while the altitudinal timberline is formed by two deciduous Nothofagus species,

the high deciduous beech, or lenga (N. pumilio (Poeppig et Endl.) Krasser), and the low deciduous beech, or ñire (N. antarctica (G. Forster) Oersted). The evergreen beech, or guindo (N. betuloides (Mirbel) Oersted), may form the timberline in the moorland region of southwest Chile.

The Falkland Islands are treeless. There is probably no climatic reason why Nothofagus could not grow there, however, as indicated by plantings (Low 1986). Efforts to establish trees on the Falklands have been limited, but several species have been tried, among them the guindo (Nothofagus betuloides), lenga (N. pumilio) and ñire (N. antarctica), and they can obviously grow on suitable sites. A few individuals of such oceanic temperate species as the Sycamore maple (Acer pseudoplatanus L.), holly (Ilex aquifolium L.), laburnum (Laburnum anagyroides Med.) and Swedish whitebeam (Sorbus intermedia (Ehrh.) Pers.) can be seen in gardens. All of these grow naturally in northwestern Europe or are planted on the Faeroes (Tuhkanen 1987).

In most mountain ranges in New Zealand, the evergreen Nothofagus species (silver beech, N. menziesii (J. D. Hooker) Oersted, or mountain beech, N. solandri var. cliffortioides (J. D. Hooker) Poole.) form the upper treeline. This line is usually abrupt and the treeline proper and the forest line coincide (Wardle 1965). In certain circumstances there is a krummholz zone, however. The South American Nothofagus treelines are physiognomically more or less similar to those in New Zealand, but the forests more often grade into dense krummholz (Wardle 1998).

This brief review shows how great is the taxonomic diversity of trees at the timberline. Many families of angiosperms and gymnosperms, hardwoods and conifers, deciduous and evergreen species are represented, including two genera of tree ferns (Hermes 1955, Troll 1973, Wardle 1974, Ohsawa 1990).

Factors regulating the timberline

The location of the polar timberline is controlled primarily by climate. Not only average climatic conditions but also climatic extremities have a strong impact on the growth of trees, although timberline trees are well adapted to severe and fluctuating environmental conditions (Hustich 1983: 182). Numerous other factors may be important locally: human activities, catastrophic events and topographic, edaphic and biotic factors. These will be discussed in more detail below.

Frost is one of the growth-limiting climatic agents. Night frosts may damage annual shoots and reduce annual growth in timberline trees. Frost desiccation threatens the trees in winter, and even more so in spring, at least those parts that protrude from the snow at the time when the days are becoming warmer and assimilation in the trees is increasing even though the soil is still frozen (Tranquillini 1979).

Wind and topographic features regulate the thickness of the snow cover, and trees exposed to high winds are susceptible to abrasion by crystals of snow and ice carried in the wind (Holtmeier 1981). Winds can also uproot trees or break them off, as seen in Finnish Lapland (Eronen 1979: 107).

The pattern of propagation, which can take place at the timberline not only sexually but also vegetatively, by layering, is one of the biological means of ensuring regeneration. Krummholz, bush-like growth forms which are either phenotypic or genotypic in origin (Holtmeier 1981), provides another means by which trees can survive and propagate themselves in extreme habitats.

Many theories and hypotheses exist regarding the climate as a determinant of the timberline (Daubenmire 1954, Tuhkanen 1982, Larcher 1984, Pears 1985). These may stress the significance of excessive light in the mountains, light deficiency, carbon dioxide deficiency, amounts of nutrients, high relative humidity, deep snow cover, wind, desiccation during the winter cold, heat deficiency and other factors, but none of these seems to adequately explain the worldwide phenomenon of the timberline.

The processes and mechanisms of plant physiology that could explain timberlines are being studied in a number of places. Many of the classic investigations have been carried out in the Alps and New Zealand. These suggest two primary causes: a negative carbon dioxide budget and developmental phases closely related to poor climatic resistance to winter conditions, i.e. completion of annual growth and reproduction cycles (Wardle 1971, Tranquillini 1979).

Taken all in all, the present location and character of the timberline as we observe it in the landscape is the result of a great number of current and historical factors and processes of different types operating on different scales (Fig. 10). The timberline is primarily controlled by climate, but it is very difficult to ascertain which climatic factor is ultimately decisive and critical for tree growth. The timberline is a manifestation of the sum of unfavourable climatic factors, but it seems that in extratropical climates, these are chiefly connected with thermal

conditions during the growing season, although it is also true that frost and desiccation injuries to buds and immature new shoots in late winter may determine the extreme limit for trees in the timberline region. As a rule, the effects of factors other than climatic ones are likely to remain of the order of some tens of kilometres in polar areas and maximally two or three hundred metres in the mountains.



Fig. 10. Factors that determine or influence the upper limits of trees and forests. The scheme is applicable to the Arctic timberline as well. (Wardle 1993: fig. 1)

Climatic characteristics and the timberline

Many attempts have been made to delimit and characterize the location of the timberline with the aid of various climatic parameters and indices. The oldest and best-known of these is the 10 °C (50 °F) isotherm for the warmest month of the year (Supan 1884, Andersson 1902, Köppen 1919). Temperature sums and lengths of various warm seasons have also been frequently used to characterize timberline.

One approach to the problem in terms of air-mass climatology has been offered by Bryson (1966) and Krebs and Barry (1970). The Arctic front in summer is located along a line that correlates well with the boundary between the boreal forest and tundra in central Canada (Mitchell 1973), and a comparable situation is seen in Eurasia. The zone of mixing of modified Pacific and Arctic air masses is narrow in the northwest and broad in the southeast, which has a certain correlation between the width of the forest-tundra zone (Bryson 1966).

Hare and Ritchie (1972) noted that the values for many radiation parameters (annual global net radiation, net radiation during the growing season etc.) rise sharply at the treeline and are associated with the zonation of the boreal and Arctic vegetation. Radiation shows a close correlation with summer temperature conditions, especially the temperature sum for the growing season (Grigor'yev & Budyko 1960) and potential evapotranspiration (Hare 1964).

It seems somewhat surprising that the occurrence of permafrost does not correlate with either the northern timberline or the boreal vegetation zonation. The forest line in northwestern Canada coincides fairly closely with the southern limit of continuous permafrost (Brown 1960, 1970), but in Eurasia permafrost extends deep into the boreal forest zone in the most continental regions (Tikhomirov 1970).

A general principle is that the northern timberline is primarily a thermal limit, although it may be significantly affected by wind, especially in highly oceanic climates. Moisture is of secondary importance (Hare 1950, 1954). Similarly, it seems that the severity of the winter is not a critical factor for the northern timberline (Fig. 11), although winter conditions may be significant in highly oceanic areas where high wind speeds and thin snow cover are the rule.

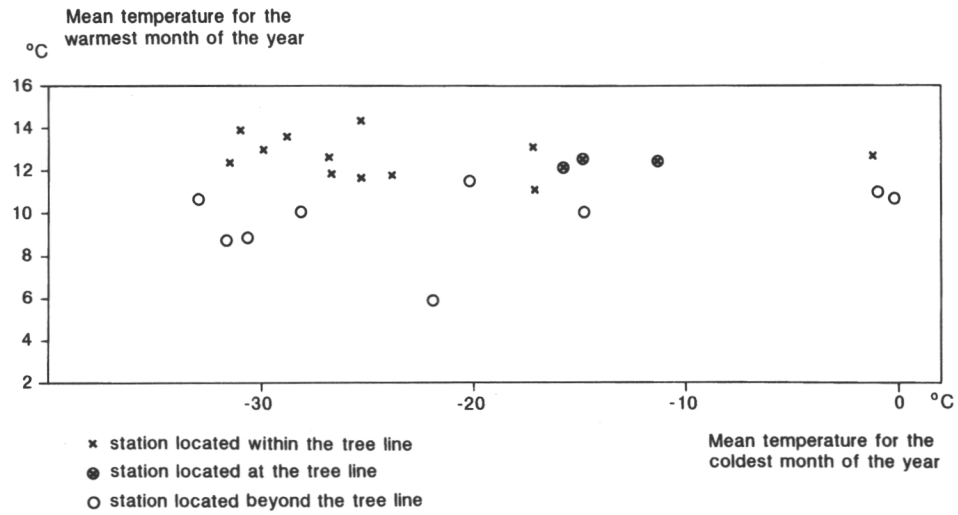

Fig. 11. Summer and winter temperatures at climatic stations located in the vicinity of the treeline in Alaska and Canada. The mean temperature for the warmest month of the year at the treeline is relatively constant at 11-12 °C (51.8-53.6 °F), but the mean temperature for the coldest month of the year varies by tens of degrees. (Tuhkanen 1982)

The 11 °C (51.8 °F) isotherm for the mean temperature of the warmest month of the year (either July or August) over the period 1931-60 is closely related to the northern treeline in the relatively maritime area of eastern Canada, and the 12 °C (53.6 °F) isotherm follows the northern treeline closely in the continental interior of North America. The curve for the 15 °C (59 °F) mean daily maximum temperature in the warmest month of the year does not coincide with the treeline any better than do the isotherms for mean temperature. The locations of the isotherms described here vary greatly from year to year, and the average values based on a normal period of 30 years are only abstractions. The 10 °C isotherm for the warmest month of the year, for instance, varies by some 1,000 kilometres in Canada over a period of no more than 10 or 20 years (Tuhkanen 1980).

The correspondence between climatic indices and the treeline (Fig. 12) is similar in Eurasia and North America, with the exception that the treeline passes north of the climatic isopleths at many points in extreme continental areas of Russia. This can be seen clearly around the Bay of Khatanga, where trees survive and grow in a 75-day growing season with a monthly temperature sum (threshold + 5 °C) of only 11.2 °C. The mean July temperature is 12.4 °C (54.3 °F) (Norin 1978), which is relatively warm for latitude 72° N.

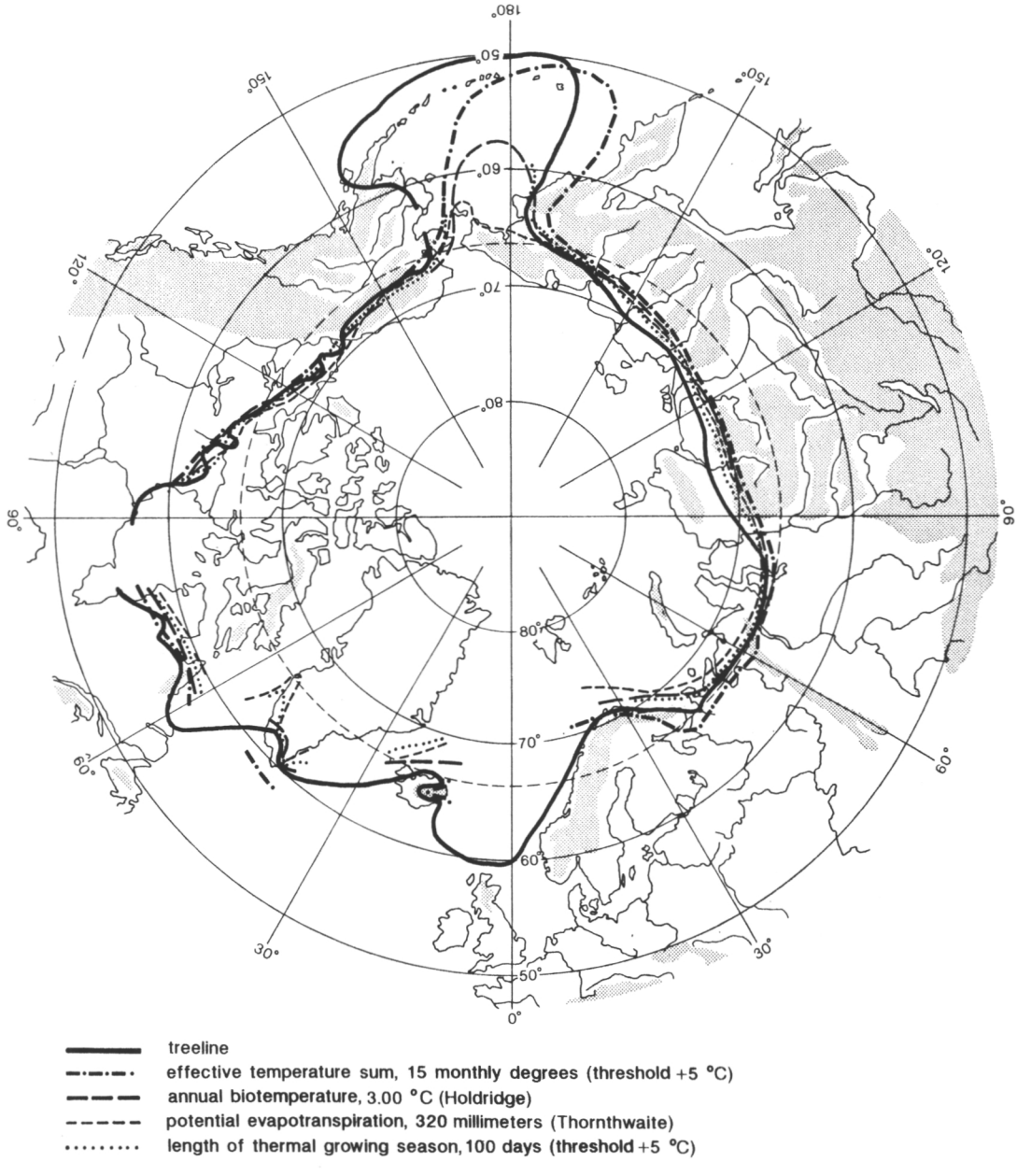

Fig. 12. Comparison between the treeline and the isopleths of certain climatic indices in the northern circumpolar area. Biotemperature according to Holdridge (1966, 1967), potential evaporanspiration according to Thornthwaite (1948). Climatic data are from Alaskan, Canadian, Danish, Icelandic, Finnish and Soviet summaries, mainly for 1931-60.

It is difficult to say on the basis of existing data that any of the parameters or indices is better than the others. All of them are satisfactory indicators of the northern treeline. The Holdridge biotemperature, roughly the sum of monthly mean temperatures above 0 °C divided by 12 (Holdridge 1966, 1967), may have some advantages, however. In Tierra del Fuego, for example, the mean temperature for the warmest month of the year at the upper treeline (upper limit of Nothofagus krummholz) is only 6 to 6.5 °C (42.8 to 43.7 °F), but the biotemperature is 2.5 to 3 °C. The growing season in a highly oceanic climate is relatively long and may compensate for low mean temperatures. Nevertheless, no formula has universal validity for all extra-tropical regions.

The isopleths described so far in general pass to the north of interesting "anomaly" regions such as Iceland, the Faeroe Islands, the Aleutian Islands and southwest Greenland. Natural forests survive in Iceland and in the southwest corner of Greenland. The Faeroe Islands are naturally treeless, but plantings indicate they are well inside the potential timberline (Ødum 1979, 1990). The Aleutian Islands may also be treeless for reasons associated with the distribution history of trees following the most recent glaciation (Griggs 1934), but Sitka spruce (Picea sitchensis) has been planted with modest success (Alden & Bruce 1989). In any event, the Aleutians should not be included in the phytogeographical Arctic zone, because the composition of the plant communities at lower altitudes is predominantly boreal (Hämet-Ahti 1981).

Widely different opinions exist on the assignment of the highly oceanic corners of the Northern Hemisphere circumpolar zone to biogeographical regions and zones, and the same is true for Tierra del Fuego or the Auckland and Campbell Islands, for example, in the Southern Hemisphere.

The vegetation of the ocean coasts and islands, and that of the hypercontinental areas, differs significantly in many respects from the "average" plant cover of the majority of the boreal zone. The anomalies are primarily sectorial rather than zonational, however, and can be interpreted as normal, representing the two extremes of the climatic continentality-oceanity continuum within the boreal zone.

Accordingly, treelessness cannot be automatically considered a decisive criterion for the Arctic or Antarctic phytogeographical zone. Each of the boreal subzones has its own treeless, or partly treeless, oceanic sector. The corresponding zone in the Southern Hemisphere, the

"antiboreal" zone, is also treeless in part. Similarly, the birch and alder forests found in humid, oceanic areas in all corners of the northern circumpolar zone can be regarded as sectorial feature, not zonational ones (Hämet-Ahti 1981). There is no reason to over-emphasize the role of trees in phytogeographical zonations.

Deviation of climate isopleths from timberlines

There are many reasons to suggest that, even if the timberline could be located unambiguously and exactly on a map, and even if it were possible to construct climatic isopleths more accurately, the timberline would not coincide perfectly with the isopleth of any one climatic indicator.

First, we are dealing only with climatic indicators and characteristics, and not with the actual determining factors for the positioning of the timberline.

Timberlines are not stable phenomena, but react even to relatively short-term fluctuations in climate. In the time known as the Little Ice Age, between the late 16th and late 19th centuries, the pine and birch limits retreated in northern Scandinavia (Kullmann 1993), while the climatic amelioration mainly in the 1930's, caused timberlines to advance in many parts of the northern circumpolar zone (Hustich 1958), only to retreat again in the 1950's and 1960's. Recent reports from Scandinavia indicate that timberlines are continuing to recede (Gorchakovsky & Shiyatov 1978, Kullman 1979, 1990, 1993, Scott et al. 1987) just as the climate of the North Atlantic region in particular has been cooling since the early 1950's (Jones et al. 1987, Alexandersson & Eriksson 1989, Koutaniemi 1990). On the other hand, altitudinal expansion of forests has been reported locally (Sonesson & Hoogesteger 1983).

Research in central and eastern Canada suggests that the timberline there should be regarded as a relict (Larsen 1972, Nichols 1976, Elliot 1979), whereas in southwestern Alaska and western Norway it is assumed that spruce has not had time to reach its climatic limit (Griggs 1934, Tallantire 1972).

The timberline is probably capable of advancing rapidly in response to an improvement in climate provided there is no topographic impediment, but it is slower to retreat in response to a deterioration in climate, because trees can live for hundreds of years without reproducing (LaMarche & Mooney 1967, Payette et al. 1985). Kullman (1990) does not support this view, however. According to him, responses to climatic cooling may be as rapid as to warming. Obviously species characteristics

such as longevity have a considerable effect on timberline stability (Scuderi 1987). At any event, the timberline is a dynamic ecotone and reacts sensitively to a multiplicity of climatic changes.

The timberline is not always determined by climate, however, as pointed out above. Anthropogenic influence has been exerted on the forests of the northern timberline regions for some centuries (Brockmann-Jerosch 1919, Hustich 1948, 1966, Ritchie 1960, Tikhomirov 1961). In Lapland reindeer husbandry, for example, has hampered and disturbed tree growth and the regrowth of forests, and the felling of trees for firewood, charcoal and building timber has reduced the timberline and turned the marginal pine forests of Lapland into treeless heaths (Hämet-Ahti 1963, Hustich 1966: 37-40, Haapasaari 1988: 142-143, Mattsson 1995, Oksanen et al. 1995; Fig. 13). Human activities frequently trigger a rapid retreat of timberlines because trees are vulnerable to small changes in the environment at their limits.

The direct destructive effect of man exerted through the felling of trees has decreased considerably in northern Fennoscandia and other northern regions during recent decades, but new types of human impact have emerged: chemical pollution of the air, soil and water, traffic across the terrain and tourism with all its detrimental consequences such as trampling and erosion (Tømmervik & Johanson 1992, Kharuk 1993, Tikkanen & Heikkinen 1995, Ukkola 1995, Veijola 1998: 101-104).

Similarly, catastrophic events such as forest fires, avalanches, and volcanic eruptions may initiate a retreat of the timberline (Hustich 1941, 1957, 1966, Hämet-Ahti 1963, Nichols 1976, Veblen et al. 1977, Payette & Gagnon 1979), although it may be able to recover naturally afterwards (Shankman 1984). Especially forest fires, either natural or started by man, have had a great impact on the polar timberline in many regions of the northern timberline zone (Sirén 1961, Eronen 1979), and such fires may trigger aeolian processes (Tikkanen & Heikkinen 1995).

Biological agents such as plant diseases or insect damage can destroy timberline trees, particularly if their health has been undermined by pollution or exceptionally cold winters (Nuorteva 1963). The geometrid Epirrita autumnata destroyed thousands of square kilometres of mountain birch forest in Lapland in 1965-66 (Kallio & Lehtonen 1973, Seppälä & Rastas 1980), and part of this area is likely to remain treeless boreal heath or a tundra-like vegetation under the present climatic conditions (Haapasaari 1988: 136).

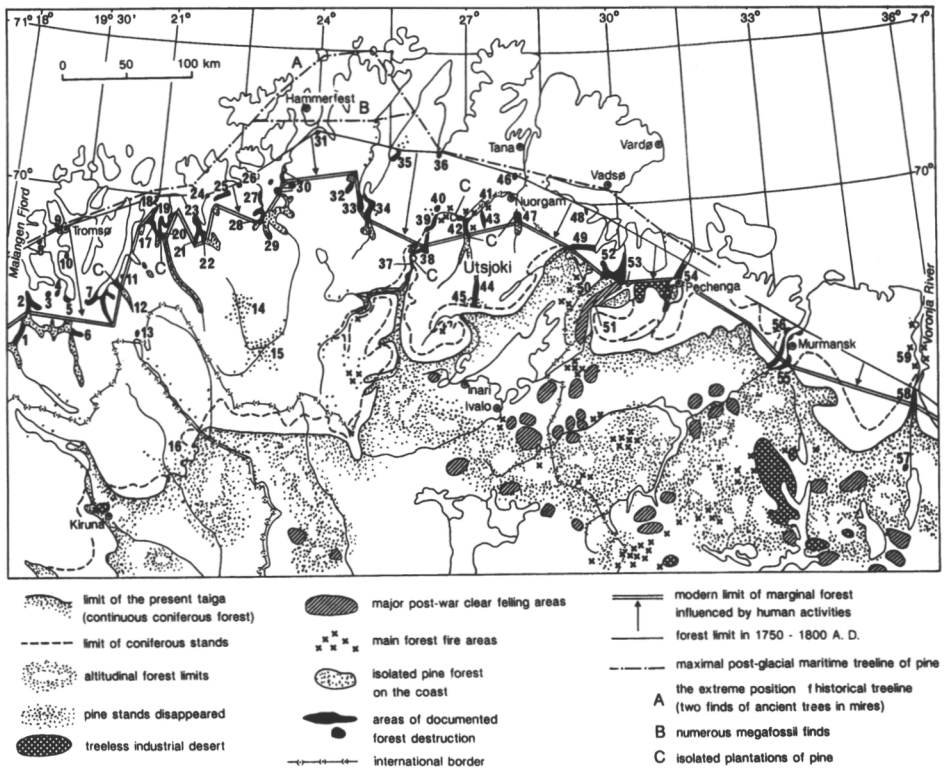

Fig. 13. Retreat of the northern coniferous timberline as a result of human activity during the last 200 years. Data were collected from 59 documentary sources. (Mattsson 1995: fig. 2)

Edaphic and topographic factors affect the position of the timberline (Timoney et al. 1992, 1993, Krzemien 1995). In rough, rocky terrain and in wet mires or on precipitous slopes, for instance, trees may not be able to thrive or take root and the timberline is forced to withdraw. It has probably also become more difficult for trees to establish themselves on account of postglacial podzolization, which has washed nutrients out of the surface layer of the soil (Eronen 1979, Timoney 1995).

The effects of all non-climatic environmental factors are likely to cause deviations from the potentially climatic timberline of the order of tens of kilometres, possibly 100 kilometres in some extreme cases, and 100 or 200 metres in the Alps.

An interesting point is that different tree species form the timberline in different parts of the circumpolar region. From a global point of view, the taxonomic diversity of the timberline is much greater. Of the tens of thousands of tree species in the world, only a small fraction, possibly a few hundred, reach the thermally controlled timberline. Nevertheless, they belong to different genera and different families and have different kinds of ecomorphological adaptations. In the light of this, it is surprising that some climatic isopleths do indicate the position of northern timberline relatively well. The same is true for both latitudinal and altitudinal timberlines in most extra-tropical regions. Daubenmire (1954, 1978) suggested that there must be some fundamental limiting factor for arborescent growth that can override differences in the ecological requirements of the various species that form the timberline around the world. He wrote (Daubenmire 1954):

"Because a great many genetically distinct trees contribute different segments of a timber-line pattern that has a remarkable geographic conformity, the hypothesis is suggested that a major autecologic principle is involved that may be analogous to the wilting coefficient of the soil, in which some environmental complex abruptly exceeds the tolerance of all trees regardless of variation among them."

A certain dichotomy exists in the literature on this point. Some researchers support the idea of a general principle behind the timberline phenomenon (Daubenmire 1954, 1978, Tranquillini 1979, Dahl 1986), but others disagree, emphasizing instead the taxonomic and ecological diversity of timberlines (Hermes 1955, Troll 1973, Hämet-Ahti 1979b).

I do not want to exaggerate the predictability of timberlines in terms of any particular climatic indicator. There are many deviations. For instance, the natural timberline formed by Siebold's beech (Fagus crenata Blume) in certain inner parts of Honshu Island, Japan, is interpreted as being in the orotemperate zone and not the oroboreal zone (Hämet-Ahti et al. 1974). In the tropics there are still more striking examples. In the Serra do Mar mountains of Brazil, for example, the upper treeline occurs at 2,000 metres, although this treeless summit area experiences only slight frosts even in winter, and 10 months of the year have mean temperatures above 10 °C (Arno & Hammerly 1984). Of course, it is possible to infer that the climatic indicators could show the potential extreme timberline if the local species assembly were different.

The timberline is an important and highly interesting biogeographical phenomenon, but as a Finnish botanist Professor Leena Hämet-Ahti has emphasized, it cannot be used as a "zero line" for intercontinental and

transcontinental comparisons of vegetation (Hämet-Ahti 1979b). Therefore, the term "subalpine" should be avoided, because it may give an erroneous impression of parallelism. Moreover, are the subalpine forests located below the physiognomic forest limit or do they include the transition belt between treeline proper and the forest limit, or is this parkland exactly the "subalpine" forest (Löve 1970)? How is the lower altitudinal limit of these forests determined? The use of dominant tree species as the only criterion is hardly enough in comparative studies. Accordingly, the meanings of the terms "subalpine" and "alpine", and possibly "subarctic" and "arctic", may not be any more than a reference to the location of a vegetation formation in relation to the local forest or treeline.

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Ussuri taiga and indigenous peoples: the passed, present and future

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History of Udege people from Bikin, Khor, Samarga regions

The Ussuri taiga and the Udege people. These are two names that cannot be separated. The Ussuri taiga has been the original and only one home of all the Udege tribes since time immemorial. As many times as this homeland has been destroyed, the residents have died as well. The past 40 years, with their intensive felling of forests, have led to a situation in which only four ethnic groups of Udege people remain. Four others (Imanka, Namunka, Kururmi, Khungari) have disappeared following the destruction of their lands and homes, part of the Ussuri taiga. Today, the remaining Udege groups face the same fate as their brothers and sisters that have gone before; logging firms, aided by international capital, are doing their best to get for themselves the forests where these people live.

Since 1990, the Bikin Udege people have opposed Russian and South Korean companies' endeavours to log the forests of the Upper Bikin Basin. The Bikin is a mountain river and the taiga in the mountains plays an important role in collecting water: in times of drought, the taiga supplies the river with water and in periods of intense rain it slows down the passage of water, thus preventing floods. The destruction of these ecosystems could lead to irreversible damage.

Certainly, we appreciate the necessity of obtaining economic profits, but not if it happens at the price of our lives and the lives of future generations. We were promised by the loggers that ecologically inoffensive Finnish technology would be used, technology that would cause minimum damage to the environment. Vehicles bearing, for us, exotic names such as 'harvester' and 'forwarder' were brought into our country. However, we can now assure you that these machines have, wherever they have been used within Primorskiy Krai, led to ruthless exploitation of the sites. This has happened to such an extent that a great deal of time will be required for its restoration. Thus, we believe that we are justified in not allowing such destruction to continue.

I do not want to accuse Finnish technology (I have no knowledge of it), but it simply seems to me that we should approach the problem timber felling not merely from the viewpoint of getting profits, but from that of ecological consequences. Unfortunately, neither the forestry officials nor the loggers have adopted this line of thinking. In is this matter that the role of the international community is so very important.

I have already mentioned our interpretation of obtaining benefits and we agreed to timber felling in the lower Bikin Basin. However, the final result was the same: the same barbaric clear-felling, the same so-called loggers taking only valuable species such as ash and leaving behind ecological destruction. Of all this the Udege people are deprived of in the surroundings but with the blessing of local authorities, and most with their assistance too, while the Udege people with their inefficient equipment have to travel far to get their construction timber and firewood.

In 1997, the first forest rental auction in Russia was held in the Khor Udege territory in Khabarovsk Krai. Then the Malaysian company Rimbunan took a 49-year lease on land, paying the sum of USD 100,000 dollars (in the form of ten vehicles) to the native community. This so-called assistance was abused by the local officials, however, in that the local community got only two vehicles with the other eight vehicles being given to non-indigenous villages. Today, this company is beginning logging in the Samarga Udege forest with the aim of having access to the sea. I am now fear that their efforts will be crowned with success as the social and economic situation in the region is very complicated: the unemployment level is almost 70% and the communication infrastructure is lacking. In the past, many attempts were made by Russian, Cuban and American companies as they dreamed about the possibility of access to these forests, but they failed.

I have already emphasised the fact that forest destruction leads to the demise of indigenous peoples; this is an axiom without any proof. However, it should be recognised that with the disappearance of indigenous peoples, their departure will speed up the process of forest destruction. In my homeland, the Primorskiy Krai, the forests have been preserved only where indigenous peoples live, where these people keep to their traditional activities.

Due to the fact that the aborigines have protected their nature, their lands have become tempting morsels for all manner of merchants. I would like to underscore again the point that we realise the necessary of using natural resources, including timber, for economic development, but also that the virgin part of the Ussuri Taiga is part of the common heritage of all mankind, a corner of the world where the degree of concentration of biological diversity is so high as to be quite difficult to find elsewhere on our planet. Ussuri Taiga is home to South and North, northern and southern endemic species live here, this is the only place where the Amur tiger occurs in its natural habitat, and now this animal has to go deeper into the forests, together with the Udege people, due to the industrial activity of white people. At the present time, the Udege people and various green organisations are co-operating in trying to put into practice the idea of imparting the status of World Cultural and Natural Heritage to the territory under the aegis of UNESCO.

It appears to me that the solution to the problem of the Ussuri Taiga reservation, taking into account the necessity of timber development, requires the observance of the following measures:

1. Direct participation by indigenous people in the control process regarding conservation measures and forest restoration.
2. Participation by indigenous people in environmental assessment before industrial development is commenced.
3. Implementation of economic projects (pilot) directed at:
   -Value-added processing of wood-based products in order to get a degree of profit under the conditions of a low level of timber development.
   -Introduction of ecologically inoffensive methods of timber extraction.
   -Forest restoration.

Forest management in the northern timberline forests

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Abstract

This article presents the concepts and models of nature-oriented silviculture for the management of timberline forests in Northern Europe based on literature and Finnish national forest inventory data. The basic idea is to follow the natural processes of forest ecosystems in silvicultural practices. Stand structure classification is based on the range and shape of stem distribution. The two main groups are even-sized and uneven-sized. A subclass of the latter, regularly all-sized, with dbh distribution resembling a reversed J, forms the basis for treatment models. This kind of structure is considered to be close to nature following the dynamics of natural mixed stands. Single tree selection and group selection with exploiting of undergrowth are the main treatments ensuring a constant tree cover on forest land and fulfilling the present and future requirements on the timberline forests: sustainability, biodiversity, resistance, stability, social benefits and multiple use. The

treatment alternatives for even-sized, one-sided forests are cutting small openings or patches and short strips shaped to fit the landscape and terrain. Adjacent uncut timber seeds natural regeneration.

1. Introduction

The timberline forests form a transition belt between the boreal forest zone and the tundra. The current situation is a result of prolonged development processes controlled mainly by thermal characteristics of the climate. At a wide interface between boreal forest and tundra, all tree species face severe climatic conditions reducing their growth and development. The forests of this boundary zone are sensitive to environmental changes such as climatic alterations, hazards and air pollutants, which can take place over a wide range of areas and in different periods. The concept of the timberline forests are not so far exactly determined but one definition could be as follows: Timberline forests consist of the belt from the boreal or alpine forest limit south- or downwards to the line where the thermal conditions of growing season are similar or worse than the average at the timberline at least twice a decade because of the annual fluctuation.

A crucial phase in afforesting process of open land in the North is the stage of crown cover closing. After that the interior of a forest stand is very different from the exterior in terms of the climatic extremes. Forest stands create ecological conditions more favourable and sheltered for trees and other biota to survive and grow. Together, the vegetation structure and microclimate gradients make the forest an ecosystem in which vertical stratification provides niches for many species (Hunter, 1990).

Commercial fellings in timberline forests are not often profitable but local people have needs to utilize forests also for timber production. However, forest management in timberline areas should strictly fulfil the following requirements: sustainability, biodiversity, stability, resistance, profitability, social benefits, multiple use and constant tree cover. This means that forestry practices should not endanger the functioning of ecosystems and their long-term production capability.

In the boreal coniferous zone the naturally developed forests are typified by the predominance of conifers and yet several broadleaved tree species occur mixed in the conifers. There is an abundance of small trees, and these are generally the youngest as well. The number of trees diminishes into bigger diameter classes (Lähde et al., 1991; Norokorpi et

al., 1994). This kind of stand structure is called uneven-sized (Laiho et al., 1995).

Biological diversity is a term used when referring to the general diversity of and variation in the flora, fauna and micro-organisms and their habitats (Hunter, 1990). When applied to the forest ecosystem, the growing stock of trees plays a central role in the formation of the habitat. Diversity of the growing stock means species abundance in a contiguous stand and intra-apecies variations in size, age and genetic composition. The spatial arrangement of the trees shows variation both vertically and horizontally. Natural stands and stands very close to being natural fulfil best the requirements of biodiversity (Norokorpi et al., 1994; 1997b).

Silviculture based on these principles and following the natural processes of forest ecosystems is called nature-oriented (Lähde, 1992; 1993) or ecologically oriented (Frivold, 1992) or close to nature (Hagner, 1992; Haveraaen, 1995). It could also be defined as diversity-oriented silviculture (Norokorpi et al., 1997a). The common aim is to grow mixed, multi-storied (uneven-sized) stands. They are considered to be closest to their natural state and development (Solomon et al., 1986; Watanabe and Satohiko, 1994).

While being more natural and suited to multiple use, the mixed, uneven-sized stands are also considered to have a high resistance (Burschel, 1992; Frivold, 1992; Stoszek, 1992; Larsen, 1995) against a multitude of natural damage such as those caused by storms, snow, fire, fungi and insects (Leibundgut, 1972; Burschel, 1992) as well as against anthropogenic damage like air pollution and its consequence, the global climate change (Schütz et al., 1986). Mixed, uneven-sized stands are also more economical in terms of their multiple use than even-aged woods (Johnson, 1984; Leak and Gottsacker, 1985; Burschel, 1992: Mattsson and Li, 1993).

This article reviews the concepts and regimes of nature-oriented silviculture in the northern timberline forests of Europe based on literature and data of Finnish national forest inventories (NFIs).

2. Dynamics of boreal forests

In accordance with the prevailed understanding, forests within the boreal coniferous zone have been believed to gradually evolve towards their climax stage. This has been thought to be a lasting state, one that would terminate in the laying waste of the forest by fire (Clements, 1916; Cajander, 1926). Succession would then begin from the bare ground, and

the new forest would gradually work again its way to the climax stage (Kuusela, 1990).

Recent studies focusing on the structure and dynamics of the boreal forests have shown that a lasting climax stage is more theory than reality (Huse, 1965; White, 1979; Spurr and Barnes, 1980; Steijlen and Zackrisson, 1986; Oliver and Larson, 1990; Sprugel, 1991). Even a violant wildfire leaves a considerable part of standing stock unscathed and able to keep the forest covered (Foster, 1983; Schimmel, 1993; Östlund et al., 1997). On the whole, disturbances caused by wind, insects and other damage lead only to the death of single trees or tree groups, releasing the undergrowth (Stewart, 1986; Hytteborn et al., 1991; Liu and Hytteborn, 1991) or providing regeneration a chance in the space created.

Biodiversity helps a forest to recover from a disturbance (Hunter, 1990; Larsen, 1995). Many endangered species, and with them the biodiversity are infallibly dependent on the continuity of their biotopes (Esseen et al., 1992). A clear felling always wipes out the forest ecosystem till an advanced stand occupies the site. Alterations in soil biology, including changes in the structure of microorganism community and declines in mycorrhiza (Amaranthus and Perry, 1987) as well as nutrient losses to stream and ground water (Martin et al., 1985) are further consequences of larger clearings except the changes in the microclimate. In timberline areas clear felling may even endanger regeneration and through it the existence of forest under harsh climate.

Wildfires take place in the Boreal zone forests of Europe from time to time but there are no accurate data on them. The statistics on all forest fires would indicate that genuine nature forest fires have been relatively rare. At the height of the slash-and-burn cultivation and tar burning period, man-made forest fires were frequent, with only decades between them at times (Tolonen, 1983; Lehtonen et al., 1996; Lehtonen, 1997). Before that era forest fires were less frequent (Lehtonen et al., 1996) albeit probably lit by man even then. Sediment studies proved the frequency of all fires to be about 70 to 700 years (Tolonen, 1983) in southern Finland. Similar results have been obtained in Sweden (Zackrisson, 1977; Engelmark, 1983). The extent of wildfires started by man has varied from a few hectares to thousands of hectares, whereas genuine natural forest fires have been limited into smaller areas.

In the early 1920's when the first national forest inventory in Finland was conducted, two thirds of stands were in a virgin state or developed untouched since natural regeneration or only slightly affected by

removing single trees (Heikinheimo, 1924). According to this material reported by Lähde et al. (1991) and Norokorpi et al. (1994; 1997c), the stands formed mixed woods in all stages of development with tree species composition manifesting wide variation. All advanced and mature forest stands also in the timberline region (the northernmost part of northern Boreal forest zone) were uneven-sized (stem distribution wider than 20 cm): moundy and irregularly uneven-sized, storeyed or regularly all-sized (Norokorpi et al., 1994). Nature has been constantly proceeding new undergrowth in accordance with the regeneration capacity of tree species and their ecological character. Forests seem to possess, independent of the different management practices, a marked tendency to continually move towards an uneven-sized structure (Laiho et al., 1995; 1997).

3. Silvicultural alternatives

3.1 Main categories

Based on stem frequency distribution, the silvicultural methods can be divided into two main categories: 1. Those aiming for a uniform structure and 2. Those aiming for a diverse structure. Under the first main category come high and low thinnings and dimension fellings. Low thinnings unify stand structure by removing smaller trees from under the canopy. High thinnings and dimension fellings aim to unify the structure from above. The dimensional thinning means only the systematic removal of trees above a predetermined size. In the second main category the original distribution into different sizes and tree species is maintained inside the stand and its structure is further directed towards ever greater diversity (Lähde, 1992). This category includes selection fellings such as single tree selection and group selection. These methods are flexible enough to accommodate, for instance, economical demands or expectations of multiple use of the forest. The size and rotation of felling coupes are not constant (Foiles, 1978). Under this category come also the management practices that aim to diversify even-sized stands.

Most trees grow according to their size, not their age (Hatcher, 1967; Tarasink and Zwiernirski, 1990). When released from underneath the dominant individuals, the suppressed trees reach the same dimensions as their counterparts growing in similar conditions but in free space. Small suppressed trees respond more readily than older ones (Vaartaja, 1951; Hatcher, 1967). Thus age is not the best criterion to describe uneven-sized stands where trees have been suppressed. It is more justified to use

size instead of age to describe the within-stand structure (Lähde et al., 1991; Laiho et al., 1995).

3. 2 Uneven-sized forest

Stands with a DBH range of at least four classes with intervals of four or five centimeters are termed uneven-sized (Laiho et al., 1995). The best results are obtained from an uneven-sized, mixed wood where the number of trees declines at a relatively steady rate as the diameter increases. The stem distribution resembles a reversed J. This type of structure is called "regularly all-sized" (Laiho et al., 1995). It is the steady state that nature-oriented silviculture strives to achive.

Nature-oriented silviculture is implemented by single tree or group selection. The latter means felling groups of trees and it is used when regeneration is specifically expected to increase the proportion of light-demanding trees. The method is therefore well suited to sites allocated to, for example, pine stands. Sites stocked with spruce and other shade-tolerant species as well as peatlands are best suited to single tree selection. However, stands with sparse undergrowth may require a heavier than normal felling.

Felling is feasible when the standing stock reaches a sufficient economical value. The felling interval varies according to the biotope and geographical location, i.e. the increment rate and usage of the stand. Normally the interval is 10–50 years. Fellings are primarily carried out on saw timber. However, some of the biggest individuals are left standing to maintain site diversity and higher vertical distribution of trees. The same goes for tree species or special forms considered rare or present in the forest only in small numbers. The aim is to remove sick and damaged trees but not all, some 10–20 trees/ha, preferably broadleaves, may be left to snag, rot and fall. In the North, old Scots pine tends to turn into barkless pine snag if allowed to die standing and dry up. It is a highly sought-after building material and in constant demand. Timber with no economic value is not considered worth felling.

Shorelines and other verges are normally left untreated or treated very carefully and slightly. They are a valuable refuge to many species and subsequently to biodiversity itself and form ecological channels (Hunter, 1990). Over-dense groups, all the way down to sapling stands, may be thinned should the recuperation and structural development so dictate, always favouring broadleaved trees in the remaining stand. Within the small openings created by single tree or group selection under the continuous cover regime, the speed of regeneration will benefit from

broadcast sowing or more favoured species. Regeneration also benefits from light soil preparation. This group selection also includes tending to the inter-group trees.

Lähde et al. (1998) have presented the guidelines for the target stem distribution after selection fellings by site type in Finland (Table 1). The models are largely based on the material obtained from the national forest inventories in Finland, especially from the 3rd NFI in 1951–1953. At that time the structure of advanced Finnish forests resembled fairly well naturally developed forest, 65 % of them being still regularly all-sized (Laiho et al., 1994). In developing the models, regularly all-sized sample plots of the 3rd NFI were selected as the basic material. Their stem frequency distributions were then calculated by site and tree species in 4-cm diameter classes. A coefficient q was used to express the ratio of stem numbers in neighboring diameter classes. In the inventory material selected for the models, q-coefficient averaged 1.6. It bore no significant relation to either the location or the site. The basal area, the q-coefficient and the number of large-sized trees determine stem distribution in the models. It was apportioned for tree species, in accordance with their proportion in the inventory material. Scots pine was the dominant tree species in the northernmost part of Boreal zone. The proportion of broadleaves was less than a quarter of the basal area in all categories, the most common of these being pubescent birch. The after-cutting models were based on all respective inventory plots, i.e. those felled recently and for a long time ago.

Table 1. The before- (bc) and after-cutting (ac) models for stem distribution (stems ha^{-1}), volume (V, m^3ha^{-1}) and basal area (G, m^2 ha^{-1}) for selection cutting of uneven-sized, mixed stands by site type in the northern timberline forests.

Site type		DBH class, cm 4	8	12	16	20	24	28	32	36	V m^3ha^{-1}	G m^2ha^{-1}
Moist heaths	bc	570	357	220	167	107	74	51	32	17	158	21
	ac	473	295	185	115	72	45	28	12	5	98	14
Dryish heaths	bc	450	340	224	142	100	67	38	21	12	120	18
	ac	375	235	147	92	57	36	22	8	4	70	11
Dry heaths	bc	427	323	227	167	123	87	47	25	11	106	16
	ac	317	198	124	77	48	30	19	5	2	56	9

The before-cutting models were calculated using sample trees of the 3rd NFI. Their height and annual radial and height increment in the last

five years were recorded. For economical reasons the removal was set as high as to 50 to 60 m^3 ha^{-1} in timberline forests. To achieve this, the basal area had to increase by 7 m^2ha^{-1} from after-cutting value. The cutting interval should be from 30 to 50 years and annual growth from 1.0 to 2.0 m^3 ha^{-1}. The models are not sensitive to the shape of the stem distribution curve. A decrease in the q-coefficient from 1.6 to 1.5 only reduces volume increment by one percent.

3.3 Mature even-sized stands

Advanced and mature even-sized stands do not respond directly to felling regimes used by nature-oriented silviculture. Therefore, limited amount of small openings are needed. Openings should be smaller than one hectare in order to preventing hazardous microclimatic extremes to regeneration and survival of seedlings. Some trees over 20 cm in DBH, such as reject of saw timber, may be left to smoulder, scattered over the area. Single broadleaved trees, together with a few conifers, are left for raptors or to rot and hollow where they stand to benefit birds, fungi and insects as they are very important to the biodiversity of the stand.

The seeding capacity of the adjacent forest should be utilized in regeneration. Conifer seeds spread out readily twice the projected height of the parent tree but many broadleaves scatter their seeds more than 100 m from the source. Heaped-up logging residue could be burnt from late autumn to early spring while there is no risk of forest fire. The regeneration may benefit from light scarification if it looks likely that it will be slower than expected. Where cultivation proves necessary, it is best carried out using broadcast sowing. When possible, a combination of natural regeneration and cultivation is used to patch up poorly seeded sites.

Sapling stands are left to develop free from clearing operations and thinnings (Norokorpi et al., 1997a) to such a size that felling under the continuous cover programme will give reasonable returns. After that the stand is treated as a mixed, uneven-sized conglomeration.

Alternative to small openings are patches and short strips. Patches are best established on tracks laid for harvesters. Strips are shaped to fit the landscape and terrain and so provide all important verges that further increase the biodiversity of the site (Hunter, 1990). A patch is never larger than 0.3 ha. No felling coupe is ever more than a quarter of the whole compartment. The next section is felled only after the previous

one has reached its first felling stage. The width of a strip is best left to vary according to the terrain but it should not be more than 25 m. The rest of the management follows the regime used for small openings. The remaining stand will provide seed for a natural regeneration.

While attempting to regenerate an even-sized stand using seed tree and shelterwood fellings, the above mentioned guidelines for clear cuttings as well as for aerial and other restrictions still apply. A seed tree area may be ecologically very similar to a clear cutting site but it is a better alternative aesthetically, and also more diverse. A shelterwood felling in a spruce-dominated stand is aimed at leaving mostly pine and broadleaved trees to form the shelter. The number of seed trees per hectare varies from 20 to 150. The shelterwood density is 150–350 stems/ha. Not all seed trees, nor all of the shelterwood, are removed but some 10–20 stems/ha are left until the young stand reaches an intermediate stage. Best policy is to leave them to die and dry standing or rot, enriching the forest ecosystem biodiversity.

4. Discussion

The studies based on NFIs in Finland showed that regular all-sizedness is the most common, natural and diverse stand structure to be found in the Finnish boreal zone. These results supports the view that forests have an inherent tendency to develop primarily towards a stand structure with stem distribution resembling a reversed J (Laiho et al., 1994; Norokorpi et al., 1994; Zackrisson et al., 1995; Lähde et al., 1998). It was therefore chosen as the basis for nature-oriented silviculture models.

Considering the structure of nature forests and the inherent development tendency of forests in general, it is understandable that forests in the Boreal zone have consisted mainly of uneven-sized mixed stands (Huse, 1965; Hytteborn et al., 1987; Pobedinski, 1988; Bonan and Shugart, 1989; Lähde et al., 1991; 1992; Chertov, 1994). Uneven-sizedness even appears to be a global phenomenon (Solomon et al., 1986; Kelty, 1989). A particular emphasis has been given to the natural uneven-sizedness of the forest in the northernmost regions of the Boreal zone (Heikinheimo, 1922; Uppskattning..., 1932; Ilvessalo, 1970; Zackrisson et al., 1995).

Nature-oriented silviculture by selection felling leads to no drastic structural changes in a forest ecosystem (Larsen, 1995; Pretzsch, 1996). This should be one of the most important demands. Small opening and

strip regeneration exhibit ecological features intermediate between the clearcutting and the selection system. Depending upon the size of the clearings the nutrient cycle remains more or less closed. Regeneration under canopy cover implies a mild disturbance with only small changes in matter balance of the system maintaining control of the nutrient cycle. Further the microclimate created by the forest cover remains almost unchanged (Larsen, 1995). A minor disturbance may even increase the biodiversity when compared to heavily treated or untreated forests (Huston, 1979). However, an undisturbed, virgin stand will have greatest size diversity among its trees, i.e. greatest biodiversity in that respect (Buongiorno et al., 1994; Laiho et al., 1997).

The estimates and surveys into timber production in uneven-sized mixed stands versus even-sized or uniform stands have produced varying results. The current opinion is that there appears to be no great differences (Schütz, 1989; Lundqvist, 1990; Kolström, 1993), or timber production is better in uneven-sized stands (Hasse and Ek, 1981; Znerold, 1987; Haight and Monserud, 1990; Lähde et al., 1994; 1998; O'Hara, 1996). There are also those who take the opposite view (Trimble and Manthy, 1966; Mikola, 1984). Yield comparisons in timberline forests are lacking so far. However, timber production in timberline forest is not the main target but to ensure a constant tree cover on forest land for present and future requirements: sustainability, biodiversity, resistance, stability, social benefits and multiple use.

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Soil properties as determinants of tree species distribution in Finnish Lapland

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Abstract

The present paper demonstrates that till soils in timberline region in Finnish Lapland vary as regards their hydraulic properties. Scots pine (*Pinus silvestris* L.) and Norway spruce (*Picea abies* Karst) differ in terms of their hydraulic site requirements, and tree species distribution in the region follows the mosaic pattern of tills. It was found that Scots pine tends to be adapted to dry tills, while Norway spruce has a wider tolerance of soil water content. The *in situ* dielectric determination of soil moisture, coupled with terrestrial gamma radiation measurements, provides a reliable ground-truth reference for the classification and interpretation of airborne radiometric data. Airborne gamma-ray data provide necessary information on soil moisture and thereby help in tree-species selection when applying artificial regeneration in forestry.

1 Introduction

Norway spruce's timberline in Finnish Lapland is located roughly 100 km south of the Scots pine's timberline. The former appears to be independent of climatic factors (i.e. temperature sum), and follows instead the geological boundary between the Central Laplands Greenstone Belt and Laplands Granulite Complex. Forestry in timberline region in Finnish Lapland is practised over an extensive,

isolated region. Forest management in the region has intensified since the early 1950s when fellings started to greatly increase. Owing to the higher productivity and timber value of Scots pine compared to other species, clear-cutting, site preparation and artificial regeneration of pine have been the predominant forest-regeneration activities applied during the past 40 years.

Serious cases of seedling dieback have occasionally occurred, the worst failures occurring in pine regeneration areas on fine-textured soils covered by a thick humus layer and formerly carrying Norway spruce as the dominated tree species (Lähde 1974, Pohtila and Pohjola 1985). Although some damage, such as frost heaving and fungus diseases, specially snow blight (*Phacidium infestans* Karst.) and Scleroderris canker (*Ascocalyx abietina* Lagerb.), have been observed in the field, the primary physiological reasons for pine-seedling dieback still remain unclear.

The main problem has been lack of techniques for classifying and mapping soils on the basis of their physical properties and for identifying sites suitable for growing the different tree species. Particle size distribution is the major factor determining the field capacity of soils (Hillel, 1971; Viro, 1962; Sepponen, 1981), and the quantity and quality of the soil matrix governs the moisture content and hydraulic properties of soil material. However, conventional sedimentation techniques (hydrometer and pipette) used in standard particle size analysis as well as conventional gravimetric techniques for measuring forest-soil moisture are too slow for use in practical soil classification and mapping. Therefore, rapid *in situ* techniques and remote sensing of soil moisture would be enormous assets in forest regeneration.

2 Materials and methods

Tills cover 75% of the land area in Central Finnish Lapland. Due to weak glacial erosion and deposition, and the presence of incorporated preglacial weathering products, the tills in the region are highly variable in terms of their hydraulic properties. A relatively thin layer of till (1-4 m) covers the bedrock in the study area. A limited proportion of stratified sandy and gravelly materials are found only in the river valleys. We studied the hydraulic properties and tree-species composition on twelve sites about 150-280 km north of the Arctic Circle. These sites, one hectare each in size, were surveyed in 1995 with terrestrial dielectric and gamma radiation measurements applying 10-metre line separation and 5-metre station separation. Since soil water content varies with respect to time, the dielectric values of the till soils were monitored once a week from 1995 through 1997. On six of the sites gamma radiation was also monitored in order to acquire someground-truth references for the airborne gamma radiation data such that half of the stations were located on fine-grained tills and the

other half on coarse-textured sandy tills. The registering period was from the end of April to the beginning of September at least once a week. Scots pine was the predominant tree species on five of the sites, with the rest of the sites being occupied by stands of Norway spruce or mixed stands of Norway spruce and pubescent birch (Betula pubescent).

2.1 Dielectric properties

The dielectric properties (ε_r) of soils are predominantly dependent on the volumetric water content (v.w.c.) of soils (Topp et al., 1980; Sutinen, 1992, Fig.1.). The dielectric properties of forest till soils *in situ* on each study site were determined over grids using time-domain reflectometry (TDR, Trace System 1, Soilmoisture Corp., Santa Barbara, CA, USA). TDR provides information of the electromagnetic wave velocity and dielectric properties of the material along a parallel transmission line. For the grid measurements, two parallel 15-cm-long steel probes spaced at 5 cm were inserted vertically into the soil. For monitoring purposes, probes were inserted horizontally into the soil layers and ε_r was determined by means of TDR (1502B metallic cable tester, Tektronix, Beaverton, OR, USA) on a weekly basis.

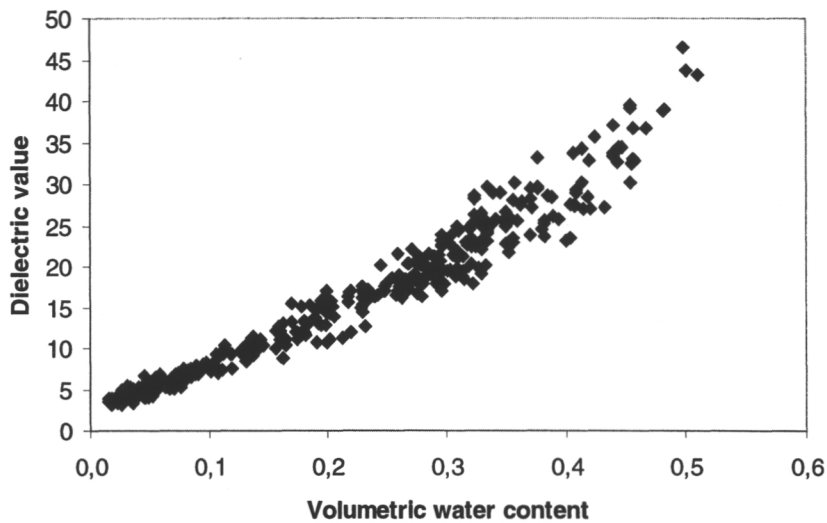

Figure. 1. A plot showing the correlation (r_s =0.98, P<0.01, n=425) between the soil dielectric values and volumetric water contents according to Sutinen (1992). An empirical relationship $\varepsilon_r = 3.2 + 35.4 * \theta_v + 101.7 * \theta_v^2 - 63 * \theta_v^3$ is obtained

2.2 Gamma ray spectrometry

All minerals, and consequently all till soils, are radioactive to some extent. The attenuation of gamma radiation is dependent on the quantity and quality of the absorbent medium and the energy content of the gamma radiation. Natural gamma radiation is effectively attenuated by water, and variations in soil moisture can be detected by terrestrial gamma-ray spectrometry (Zotimov 1971). For example, a 50% attenuation of the radiation in a potassium energy window occurs in about 100 m of air, 10 cm of water, and 5 cm of rock.

The low-altitude, aerial geophysical surveys carried out by the Geological Survey of Finland consist of the recording of the total magnetic field, in-phase and out-of-phase components of the electromagnetic field, as well as gamma radiation. These airborne surveys have been conducted since 1972. The flight altitude varies from 30 to 50 m with flight-line separation of approx. 200 m. The data recording speed, 1-4 times per second, and a flight speed of 50 m/s, permit data-recording spacing of 10-50 m. The airborne gamma ray data are recorded by means of a gamma spectrometer equipped with six NaJ(Tl) sensors with a volume of 25 litres. The gamma spectrum of 0.3-3.0 MeV consists of 120 channels with 24 keV. The measuring range is divided into four windows: total, potassium, uranium, thorium (Table 1). This is the most common distribution because 42% of the gamma radiation of rocks is obtained from K^{40} isotope, 32% from Th^{232}, and 25% from U^{238} isotopes (Grasty, 1977).

The terrestrial gamma radiation data were obtained using a 256-channel gamma spectrometer (GS-256, Geofyzika Brno, Czech). The volume of the NaJ(Tl) sensor of the instrument is 0.35 litres and a four-window division, analogous to the aerial data, was used (Table 1). The detector diameter is 3.5 cm, thus allowing point-specific radiation detection.

Table 1. Energy contents of air-borne and terrestrial gamma-ray spectrometers.

Window	**Air-borne (MeV)**	**Terrestrial (MeV)**
Total count	0.30 - 3.0	0.83 - 3.0
Potassium	1.36 - 1.56	1.36 - 1.53
Uranium	1.66 - 1.86	1.65 - 1.86
Thorium	2.41 - 2.81	2.48 - 2.74

2.3 Hydraulic conductivity

Vadose zone hydraulic conductivity (K) was determined using constant head infiltration along with automated dielectric measurements using TDR (CS-615 probes with CR10 data-loggers by Campbell Scientific Inc., Logan, UT, USA). K-values were calculated by Darcy's law by deriving the pressure-potential gradient from the water pressure and the soil suction. Darcy's law was originally conceived for saturated flow only and was then expanded by Richards (1931) to include unsaturated flow. Unsaturated conductivity is a function of the matric suction head, $K=K(\psi)$, and Darcy's flux, $q=Q/A=-K(\psi)\nabla H$, where ∇H is the hydraulic head gradient, which may include both suction and gravitational components.

3 Results

3.1 Spatial variability

The dielectric and gamma data obtained from the twelve sites showed the water status to be significantly different from site to site (Fig.2). Low mean dielectric values, $\varepsilon_r<13$, and high mean gamma (potassium window) values, $\gamma>1$ (potassium window), were observed on sites naturally occupied by Scots pine stands. In contrast, high mean dielectric values, $13<\varepsilon_r<35$, and low mean gamma values, $\gamma<1$, were typical of sites occupied naturally by Norway spruce stands. The spatial variability of the sites, according to semi-variogram models, ranged from 20 to 150 m (Sutinen and Hänninen 1997).

The dielectric data are representative of the hydraulic conditions at the soil surface such that the dielectric information represents the uppermost 15 cm layer. Also, most of the gamma radiation resulted from the till soil and radiation intensity depend on the concentration of radioactive emitters in the soil, texture and soil water content. Natural gamma radiation is effectively attenuated by water. Previous experiments (Zotimov, 1971) have indicated that the water content in the soil to a depth of 50 cm can be determined by measuring the gamma field of the earth. It is suggested that an increase of 10% in soil moisture causes a reduction of 3% - 5% in ^{40}K counts. The radon effect is most insignificant on the ^{40}K channel.

The terrestrial gamma radiation data are related to the dielectric properties of the soils on the studied sites. The plot (Fig. 2) clearly indicates that soils with a high dielectric values, and consequently high v.w.c., have low gamma values due to powerful attenuation. It was

observed consistently that soils with low dielectric values and low water contents have higher gamma radiation values. Till soils with high water contents in Central Lapland are typically derived from fine-grained schistous rocks of the Central Lapland Greenstone Belt. The matrix of these tills contains enought silt and clay size particles to effectively prevent water from percolating through the soil sequences. Precipitation water presumably passes directly into the streams and rivers as surface run-off. The tills on the sites occupied by stands formed by Scots pine are coarse-textured and sandy in matrix. These tills are predominantly derived from coarse-textured granitoids.

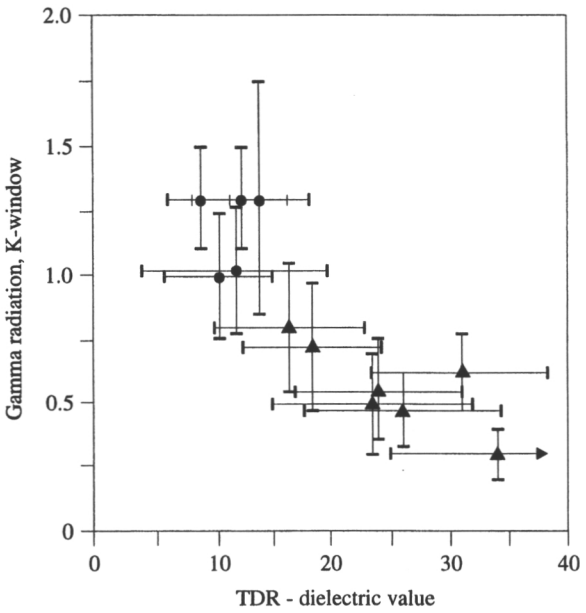

Figure 2. A plot for demonstrating the terrestrial gamma radiation vs. TDR dielectric data of forest till soils in Central Lapland. Each site was subjected to 220 TDR measurements and 110 gamma spectrometer measurements. The dots indicate the sites occupied by Scots pine stands, and triangles the sites occupied by Norway spruce stands.

3.2 Timewise variation

Our monitoring results showed that ^{40}K counts were more than 1%K on sites predominantly occupied by Scots pine (Fig. 3) whereas the counts were less than 1%K on sites occupied by Norway spruce (Fig. 4). Similarly, the dielectric values were low on the pine sites, so that the mean dielectric was ε_r<13-15 through the growing seasons (from June through September) in 1995 and 1996. Contrary to this, the sites occupied by Norway spruce were high in terms of their soil water content during the growing seasons. The most pronounced feature was

several weeks long saturation following snowmelt The greatest variations in gamma radiation intensity were observed in fine-grained tills in the early summer due to frost and snow melting Sutinen et al. 1997). Gradual soil warming and drying resulted in increasing levels of gamma radiation. Concurrent maximum gamma radiation values with maximum soil temperature occurred in mid-August. The difference between minimum and maximum values of ^{40}K counts was at least double of the minimum value at every station. Heavy rainfalls caused reductions of 10% - 20% in the ^{40}K counts. The second critical period with regard to gamma radiation is in autumn when the soil cools, evaporation is reduced, and the probability of rain increases.

These data showed that interpretation of aerial gamma radiation data calls for knowledge of the basic level of the gamma radiation in the study area. Dielectric detection was found to be a reliable ground-truth reference and the quantity of ground measurements required varies from one lithology to the other. Another important factor is the flight date. Aerial surveys in Finland date back to the 1970s and the basic level of radiation has varied annually. Therefore, the most reliable results can be obtained when the flight data from each year are processed and classified separately. From this standpoint, the aerial mapping of the moisture content of forest soils is possible on the basis of aerial gamma radiation data.

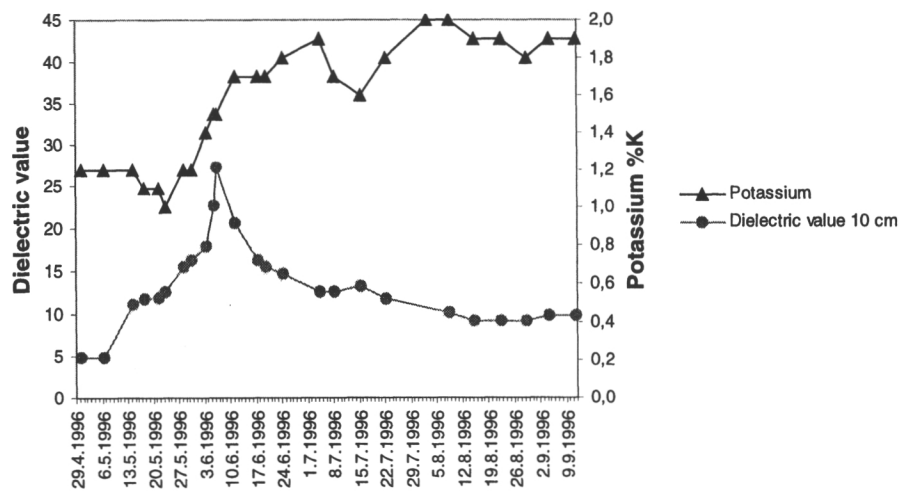

Figure 3. An example of the time-based variation of gamma radiation (potassium window) and dielectric values on a till site carrying a naturally-established stand of Scots pine.

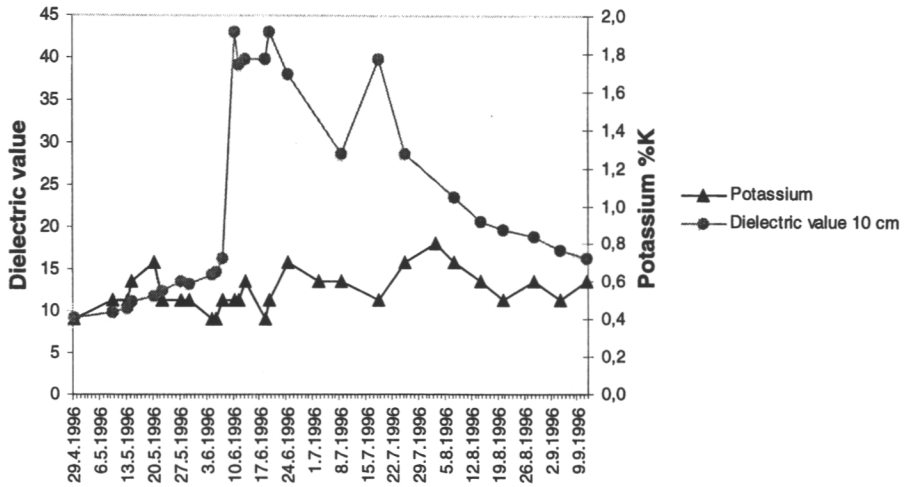

Figure 4. An example of the time-based variation of gamma radiation (potassium window) and dielectric values on a till site carrying a naturally-established stand of Norway spruce.

3.3 Hydraulic classification

Water content, matric potential, gamma radiation and dielectric values that change with time, are also controlled by the texture and structure of tills. The measured matric potentials, however, were significantly different between the till sites occupied by Scots pine (-5kPa<ψ <-17kPa) and those occupied by Norway spruce (-0.5kPa<ψ <-8kPa) (Siira 1998).

Hydraulic conductivity is a property determining how rapid the changes in water content are after rain and snowmelt. Under field conditions, the maximum value of hydraulic conductivity may be only about half of the saturated hydraulic conductivity (Stephens, 1996) Good correlation was observed between unsaturated hydraulic conductivity and soil dielectrics (r_s =0.80, P<0.01, n=16, Fig. 5), and between hydraulic conductivity and gamma radiation (r_s =0.79, P<0.01, n=12; Fig. 6). Linear regression in both cases was statistically significant with R^2=0.79 and R^2=0.82, respectively. The highest hydraulic conductivity values (10^{-5} <K<10^{-7} m/s) were observed to be typical of coarse-grained sandy tills where Scots pine stands predominate. The lowest K-values (10^{-7} m/s<K<10^{-10} m/s) were recorded for fine-grained tills. Scots pine is lacking on these till soils,

which are covered by Norway spruce and/or mixed stands of spruce and pubescent birch.

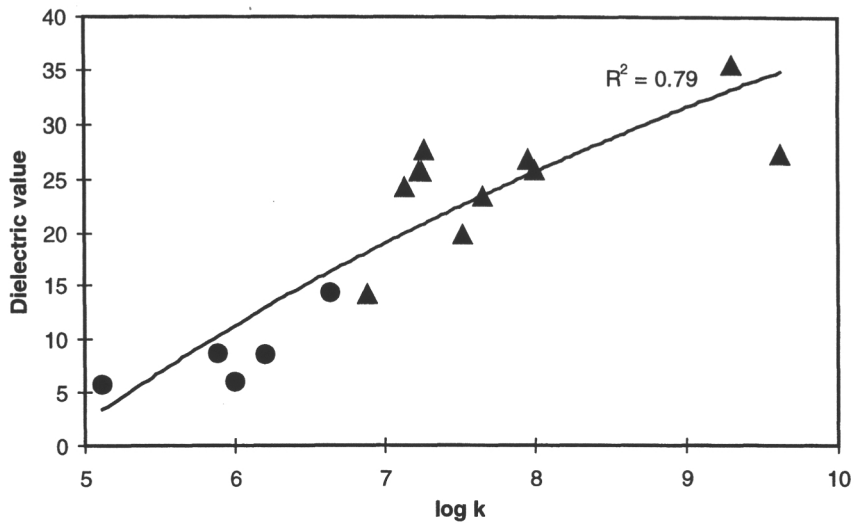

Figure 5. The relationship between *in situ* dielectric values and vadose zone conductivity (log scale). The symbols are the same as in Fig. 2.

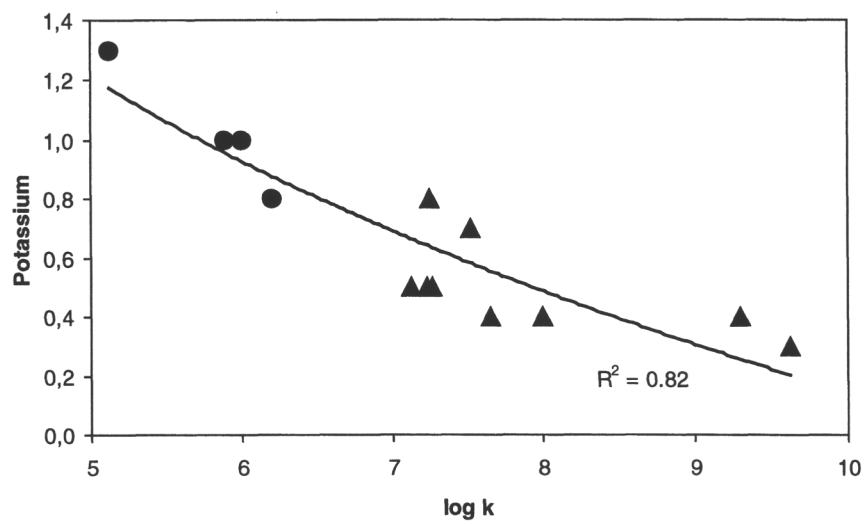

Figure 6. The relationship between *in situ* gamma radiation (potassium window) and vadose zone hydraulic conductivity. The symbols are the same as in Fig. 2

4 Discussion

Terrestrial dielectric moisture detection is a fast and reliable technique for conducting detailed surveys of forest soils. Even if laboratory tests with frequencies higher than 1 GHz indicate slightly different texture-dependent relationships between dielectric properties and v.w.c. (Ulaby et al. 1986), our *in situ* results obtained from Central Lapland, and also elsewhere (Sutinen et al. 1991, Sutinen 1992), suggest that dielectric variation and respective variation in soil water content between different types of till soils are high enough to enable classification of forest soils.

The main part of the gamma radiation is obtained from the uppermost half metre of soil (Grasty 1977) and the said radiation is dependent on the density of the rock and unconsolidated earth materials. The density of the till in Central Lapland varies between 1.4 - 2.1 g/cm^3 (Nieminen 1985), and thus 90% of the radiation is obtained from the uppermost 35-45 cm layer. Therefore, better correlation would be achieved between dielectric and gamma data one were to use the dielectric logging averages of the uppermost 40 cm. However, aerial surveys produce average gamma values for oval areas 110 m in longitudinal diameter, whereas terrestrial measurements represent only points. The interpolated aerial imagery is only feasible for general-scale overviews of the variation in forest soil moisture (Sutinen et al. 1994). Gamma radiation and dielectrics are both time-based variables and therefore the best results would be obtained if the flight data for each year were to be processed and classified separately.

The present paper shows that till soils derived from fine-textured schistous rocks in Central Lapland have high water content, which is indicated by high dielectric values (ε_r>15), low gamma radiation values (^{40}K counts less than 1%K), and low hydraulic conductivity (K<10^{-7} m/s) values. These tills are generally occupied by naturally regenerated Norway spruce and/or mixed stands of spruce and pubescent birch. In contrast, Scots pine naturally occupies till sites with low dielectric values (ε_r<15, Sutinen et al. 1997), high gamma radiation values (^{40}K counts more than 1%K), and high hydraulic conductivity (K>10^{-7} m/s).

The site requirements of Scots pine and Norway spruce are different. Therefore, some of the failures in artificial regeneration using Scots pine may be attributed to high soil water content. The rate of seedling mortality in the early stages of regeneration appears to increase along with an increasing soil water content (Sutinen et al. 1994). From the physiological point of view, the roots of pine seedlings may suffer from lack of oxygen in silty till soils, and hypoxia is suspected to be one reason for the damage. Hydraulic conductivity in moist to wet silty till soils in Central Finnish Lapland appears to be very low, and much of the excess of rain water is lost through surface run-off. This may partly promote the hypoxia effect in the early stages of stand development. Presumably the moisture content in the tilts

produced by forest-regeneration ploughing gradually increases as a result of compaction and the realignment of the capillary pathways in the tilts. This may explain the cases of pine seedling dieback 10-20 years after ploughing.

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Conflicts between Yamal-Nenets-reindeer husbandry and petroleum development in the forest-tundra and tundra region of Northwest Siberia.

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Yamal Peninsula represents a rather closed natural system in the north of the Tyumen Oblast, concentrating in mineral wealth large stocks of gas and gas condensates. In the 20th century, traditional types of management on the peninsula remain reindeer herding, hunting and fishing. This has allowed a balanced coexistence of the person and nature, via rather constant numbers within the able-bodied migratory Nenets population (1910-1913 ca. 3000; 1991 ca. 4000 persons) and dynamic changes in general increasing population of reindeer. Even fallout of radioactive pollution at the end of the 1950's and early 1960's had a negligible effect on this balance. The natural complex of Yamal, in conjunction with the local indigenous community, is characterized as being in equilibrium, though with only minimal stability. It is obvious that this ecological balance is facing real threats, due to the massive influx of the industrial workers; construction of industrial objects, gas pipelines, transportation corridors; and the uncontrolled use of vehicles (i.e, tractors) which are not adapted to local conditions and cause extensive damage to the pastures of reindeer. At the same time, recent decades have witnessed the approach of 'civilization' and global ecological changes which increasingly threaten the existence of the traditional image of Nenets life and the unique ethnic culture. As a result, the local indigenous population has felt a loss of power and become aggravated. It is therefore necessary to obtain knowledge of the initial condition of natural systems and to organize means to control the numerous ecological threats facing the region. As of today, the

construction, infrastructure and other activities related to the gas deposits in the Yamal regions of Bovanenkovo and Kharasavei have in large part ceased. It is necessary to use this hiatus for the analysis of the fragile nature of Yamal.

Since 1990, research has been initiated on the processes of socio-economic and political development of the indigenous population of Yamal, its history, material and spiritual culture. To date, many results have been attained in this regard. Using the data lists of the population from 1897 to present, the socio-economic dynamics of the so-called 'small peoples' of Yamal have been investigated. In particular, the economic development of the territory before the occurrence of oil monoculture, and history of industrial development of the Soviet North as a whole, have been studied. At a modern linguistic level are described northern Samoyedic languages (Nenetskii, Enetskii, Nganasanskii, Selkupskii) and Ob-Ugrian languages (Khanty and Mansiskii). Numerous archaeological expeditions have taken place on Yamal from 1988-1997. Analyses of recently discovered materials have greatly aided historians. Investigations of archaeological monuments, cult worship and sacred places of the indigenous population are undertaken with the purpose of maintaining their protection under conditions of development and operation of the gas deposits.

Scientific investigation of the natural environment has become of special importance and purpose after acceptance and subsequent ratification by Russia of the convention OON about biological diversity (1992). By agreeing to its rules, Russia is obliged:

- To develop national and regional strategies of preservation of biodiversity;
- To carry out inventories and to create a system for monitoring biodiversity;
- To encourage and stimulate the investigation of biodiversity;
- To prevent acceptance of the political and economic decisions, conducive to the reduction of biodiversity.

Investigations of the contemporary terrestrial and aquatic ecosystems of Yamal have revealed: 109 species of birds; about 40 kinds of small mammals; about 80 marine and freshwater fish; about 2000 soil and 200 aquatic invertebrates; 220 vascular plant taxa; more than 200 species of mushroom; and 302 aquatic plant taxa. The relative biodiversity of Yamal on a global scale is insignificant, but does include some rare, ecologically vulnerable species, making a uniform regional complex. About 10 kinds of birds and small mammals and seven vascular plants are included in the Red Book, and it seems that none appear there due to being understudied. The richest diversity on the peninsula is that among

birds, which can be attributed to the presence of a high number of global centres for nesting migratory waterfowl - geese, ducks, waders, etc. Due to a unique hydrological system, the Yamal comprises one of Arctic's centres for distribution of whitefish. The so-called 'technogenic' impact on nature, connected with the development of gas deposits, is associated, as a rule, with local reductions in biodiversity. Unfortunately, the accompanying hunting and fishing pressure is not limited to local scales and results in a significant loss of fish valuable to trade, as well as many varieties of birds and small mammals. Perhaps most vulnerable to anthropological of influences is the biodiversity of freshwater ecosystems of Yamal. An evident example is the sharp decrease in populations whitefishes. Nevertheless, the scientists of the Institute of Problems of Development of the North at the Siberian Branch of a Russian Academy of Sciences have come to a conclusion: that the natural condition the ecosystems of Yamal resulting from industrial of development is not considered critical.

At the same time, in the academy's conclusions, the researchers ascertain that "the poor condition of the vegetative communities in the region of industrial development is associated with a sharp increase in the loading of pastures frequently visited by reindeer herders near such infrastructure". They further assert that "visiting intensity by reindeer herders in the vicinity of Bovanenkovo, which is heavily exploited by virtue of being the only trading post ("the sole consistently inhabited structure") in the region, has resulted in extensive transformation of pastures due to the rapid replacement of low productivity communities by more productive grass-dominated communities".

Such conclusions are fundamentally incorrect. In truth, Bovanenkovo - on the Mordiyakha River up to the river Kharasavei - occupies extensive territory along the river and within this territory occurs extensive infrastructure, including dozens of temporary settlements, warehouses of drilling muds and other materials, drilling pads, etc., etc. This is the case rather than a single trading post as "the sole constant inhabited item in this region", as is written by the academy's scientists.

Quarries, which are used to take sand for construction of these settlements and roads between settlements, are easily seen from helicopter in the summer as scars and wounds on the fragile tundra of Yamal. As there becomes more temporary settlements in the region of Bovanenkovo, the further from them cease Nenets reindeer camps, because:

1) On the Nenets' lands survey crews and geologists excavate the ground and from these areas emanate pollution and illnesses, dangerous to both reindeer and people;

2) There are polluted pastures, lakes and rivers heavily polluted by petroleum and chemicals (i.e., drilling muds), so that lands which were formerly productive have become sterile in the past 10 years;

3) There is a great deal of poaching of domestic reindeer by the representatives of "civilization" (oil/gas workers, geologists and survey crews), which are known for their generally reckless, often drunken, behaviour.

Reindeer herders of the state farm (or Sovkhoz) "Yarsalinskii", which manages those reindeer herds grazing in the vicinity of the Bovanenkovo Gas Field, have for many years been violating the Sovkhoz's borders by allowing their animals to graze extensively on pastures administered by the state farm "Yamalskii". All this is conducive to furthering the conflicts between reindeer herders working for the state farms and those acting as private reindeer herders. These violations appear to start a chain reaction, leading to more violations, as in the Tragedy of the Commons (Hardin 1968). This is because formerly in the tundra even when there were 'reserve' pastures, which no longer exist, there was never any 'free' land, meaning that all potentially suitable pastures were, in fact, administered by someone. Previously we referred to some impacts, such as radiation, which neaarly imperceptibleand resulted in minimal damage. However, in the past two decades the many negative consequences associated with the development of gas deposits on Yamal have rendered there influence to all spheres of life in the tundra, including socio-economic and political situations.

Russian scientists attempt to calm the public by claiming that "good parameters have been provided for the recultivation of disturbed or denuded territories by using different varieties of grasses". But neither Nenets or Russian people really fooled by such proclamations. They know too well that the government has historically been responsible for environmental catastrophes such as 'Aral', the large, misguided project to cultivate cotton and corn which eventually drained the Aral Sea. Furthermore, any introduced grasses do not actual heal, much less restore, those denuded areas on Yamal, which have remained long after the earliest phases of development at Bovanenkovo and other deposits.

We understand that the Russian scientists appreciate that Gazprom has often aided their investigations logistically and financially, for example by publishing an edition of two volumes entitled "Natural environment of Yamal" (Tsibulsky et al. 1995). However, such actions do not go far enough towards repairing the serious impacts which have resulted from industrial development. Sadly, an accelerating trend among representatives of both government and scientists is to cast most of the blame regarding surface disturbances and vegetative cover on

'overgrazing' by the reindeer. In truth, there are many pastures in poor condition but, according to the Nenets, this has largely to do with the displacement of animals from previously utilized pastures that have recently been rendered unfit by industry. In the future, Nenets will need a larger measure of property rights so they may share in the decisions that will govern further development on Yamal.

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Northern timberline forests - a review

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1. Introduction

The boreal forest and the Arctic tundra are two major biomes, which cover a total of 30 million square kilometers in the Northern Hemisphere (Sirois 1992). Despite the lack of knowledge of the exact mechanism involved, there is general agreement that thermal characteristics of the climate (the low temperature limits of forest and tree growth) are of major importance in determining the northern edge of the boreal forest (e.g. Sirois 1992, Wardle 1993, Tuhkanen 1993, Holtmeier 1997). Although the position of the timberline is primarily dependent upon the climatic condition, forest fires, plant diseases, insect infestation and human activities are also of noticeable importance (Heikkinen 1984). The northern timberline is formed by evergreen and deciduous conifers, especially in continental areas, and usually by broad-leaved species in oceanic areas (Nikolov & Helmisaari 1992, Tuhkanen 1993). There are about ten noteworthy tree species forming the northern polar timberline (Nikolov & Helmisaari 1992, Tuhkanen 1993). In relation to the number of tree species in the world, or even in the boreal forest zone, this is a small number (Tuhkanen 1993). Timberline forests are rich of lichen (Ahti & Oksanen 1990) and are important habitat for reindeer and caribou (Okotetto & Forbes, Gower; in this volume).

In recent years, interest in the forest-tundra, or tree line has risen due to concern over the effects of global warming (Timoney et al. 1992). The forest-tundra may be a sensitive indicator of climatic change (Kellogg & Zhao 1988). Studies predict a northward migration of the forest-tundra of from 300 to 400 km in eastern Canada (Zoltai 1988) and an overall shrinkage of 58% due to northward enrichment by grassland and boreal forest (Rizzo 1988). Also, forest expansion into tundra would occur westward on the Seward Peninsula in Alaska (Juday et al. 1998). The Seward Peninsula is unusual in that it offers relatively modest topographic barriers to tree growth, and should the climate warm

sufficiently, a considerable land surface would be converted to forest. Subsecuently, a conversion of the Seward Peninsula from tundra to forest vegetation would result in dramatically decreased production of palatable forage species for reindeer and caribou (Babcock et al. 1998). Northern tree-line dynamics in a changing climate would be secondarily modified by altered fire regimes with all the accompanying changes in ecosystem structure and function (Weber & Flannigan 1997). Fire regime as an ecosystem process is highly sensitive to climate change because fire behavior responds immediately to fuel moisture, which is affected by precipitation, relative humidity, air temperature, and wind speed (Weber & Flannigan 1997).

The great diversity of approaches and criteria, which have been used for the characterization and the subdivision of the boreal forest-tundra transition zone has resulted in a non-unified terminology (Ahti et al. 1968, Hustich 1979, Tuhkanen 1984, Circumpolar arctic vegetation mapping workshop 1994, Tasanen & Veijola 1994, Veijola 1998a, 1998b). An ecological synthesis of the circumpolar boreal forest-tundra transition zone has not yet been produced (Sirois 1992, Kankaanpää & Vormisto 1998). The diversity of tree species, the limited knowledge of vegetation history and of the ecological processes taking place over this large area, as well as linguistic barriers with Russian literature, make it difficult to attempt a unified treatment of this transition zone as a whole (Sirois 1992). The same is true with the definition of the Arctic area. Universal agreement as to where the Arctic begins will probably never be reached: redefinition to suit individual objectives of study may always be required (Larsen 1980). The circumhemispheric timberline belt shows latitudinal and altitudinal vegetation zonation which is similar in many regions (e.g. Hustich 1966, Ahti et al. 1968, Sirois 1992).

This review tries to summarize the present knowledge on northern timberline forests in the circumpolar area. The terms used to define a timberline forest differ between arctic regions; for example in Russia timberline forests are called pretundra forests while in Canada and Alaska the names forest tundra or lichen woodland are most commonly used. Although no single study provide an overview of this issue, vegetation comparisons have been made possible as proposed by Igor Lysenko's article in this volume. In Russia the protected belt of pretundra forests extends 100-150 km south from the tundra, while in Alaska and Canada there is apparently no special justification for protection of timberline forests. In Greenland and Iceland all forests may be defined as timberline forests. This review will firstly show the locations and describe the terminology of timberline forests used in different Arctic countries. Finally, the impact of grazing and insect damage on mountain birch forests is exemplified by a case from Fennoscandia.

2. Canada

The zonation of the northern vegetation east of the Hudson Bay is characterised by the northern boreal forest that ends at the northern limit of continuous forest as lichen-woodland, then the forest-tundra where the forest only partially covers the potential sites (Sirois in this volume). Prior in the study completed by Timoney (1988), there had been no comprehensive study of the vegetation and terrain of the subarctic forest-tundra west of Hudson Bay (Timoney et al. 1992). Although tree-line maps have been produced in one form or another, by various author (e.g., Hustich 1966, Thomas 1969, Hare & Ritchie 1972, Rowe 1972, Larsen 1974, Noble 1874, Nichols 1976, Elliott-Fisk 1983, Edlund 1987, Thannheiser 1987, Ecoregions Working Group 1989), many studies have been based on a minimum of ground and airborne observations. Primary works in which original data are presented are few. Much of the geographic of northern vegetation is derivative, based on secondary sources of data (Timoney et al. 1992) (see, however, Tasanen in this volume).

The forest-tundra, the tree line, and other subarctic-arctic boundaries have been defined more often than they have been mapped. Thus it is often unclear, or left unstated, what data were used and what criteria were applied to delimit the tree line, tree limit, or the northern and southern limits of the forest-tundra (Timoney et al. 1992). Of various criteria used to delimit the forest-tundra, emphasis has been placed on the height, stem density, and growth forms of tree species (e.g. Payette 1974, Scott et al. 1987) and the typical vegetation and soils of mesic or upland sites (e.g., Bradley et al. 1982, Ecoregions Working Group 1989). Larsen (1989: 29) has defined the forest tundra transition as "that land where . . . unbroken forest occupies less than 75% of the land surface above the water table (upland), or less than 75% of the area is unbroken tundra, i.e., 25% of the land area or more is occupied by an admixture of forest and tundra."

Here is a brief essay (prepared by the Canadian Forest Service 1995) on the diversity of Canada's timberline forests, based upon "Forest Regions of Canada" by Stan Rowe:

Given the extent and the diversity of Canadian timberline forests, there is no single study providing an overview of these forests. Data on timber production in these areas are not readily available as forest classification systems used in the various provinces/territories for forest inventories do not include a "timberline forest" category. Canadian

Forest Service suggest that criteria and indicators (C&I) for timberline forests be drawn also from the Montreal Process and the Canadian Process.

Canada has two types of tree line forests: i.e. the *subalpine forests* of the western Coast Ranges and Rocky Mountains, which are traditional to alpine tundra; and ii) an extensive subarctic zone, or boreal barrens, which are transitional to arctic tundra (*forest-tundra transition).* Logging is common in the subalpine forests. There is growing concern about poor regeneration in some subalpine forest clearcuts, and a research program to study partial harvesting alternatives is in progress in British Columbia, Subarctic forests are not harvested, apart from limited cutting of white spruce along rivers such as the Mackenzie. These forests are home to indigenous people who harvest caribou and other species, and wildlife conservation is a dominant concern.

The publication Forest Regions of Canada, by J.S. Rowe, regocnizes three sections of *subalpine forest*: East Slope Rockies, Interior Subalpine, and Coastal Subalpine. The East Slope Rockies section is dominated by Engelmann spruce, alpine fir, and lodgepole pine. These all have boreal counterparts (white spruce, balsam fir, and jack pine) with which they hybridize. Lesser species include alpine larch in the south, and whitebark pine, which is often conspiocuous on exposed ridges and slopes at tree line. The Interior Subalpine section occupies extensive areas of northern interior British Columbia , and has fragmented occurrences on mountain slopes further south. It is dominated by Engelmann spruce, white spruce, and their hybrids; alpine fir becomes increasing abundant at higher elevations. Black spruce is also found in the northeastern portion of this section adjoining the boreal forest. Other species locally present include whitebark pine, western and mountain hemlock, alpine larch, amabilis fir, western red cedar, and western white birch. The Coastal Subalpine section lacks spruce species. It is dominated by alpine and amabilis fir, and mountain hemlock, with scattered occurrences of yellow cypress. It is transitional to the true Coast Forest at lower elevations. Logging is made difficult by steep slopes and limited access.

Of the 45 sections or sub-sections of boreal forest recognized by Forest Regions of Canada, eight are considered to be part of a *subarctic boreal transition zone* occurring between closed boreal forest and tundra. The southernmost zone of subarctic forest is the Hudson Bay Lowlands, with extensive muskeg and patterned fens dominated by stunted black spruce and tamarack. Riverbanks are lined by more diverse forests which include white spruce, balsam fir, trembling aspen, balsam poplar,

and white birch. White spruce tends to replace black spruce on the shorelines of Hudson and James Bays. The Hudson Bay Lowlands are characterized by calcareous, marinederived clays covered by extensive peat deposits. The Newfoundland-Labrador Barrens include extensive areas of sparsely forested heathlands and moss bogs, with tree cover dominated by black spruce upland barrens, bogs, muskeg, lakes, and rivers, with limited occurrence of balsam fir and white spruce, and infreguent white birch and balsam poplar. Permafrost is common. The Fort George area is distinguished by more extensive areas of closed stands; jack pine occurs on low, stony morainic ridges.

The Northwestern Transition is a very large band of subarctic woodland which extends from Hudson Bay almost to the Mackenzie River delta, bounded on the south by Lake Athabasca and Great Slave Lake, and on the north by Great Bear Lake. Black spruce is again moist common, mostly in open stands of dwarfed trees; white spruce occurs on well-drained soils; tamarack becomes increasingly common in the northern portions of the section. Stunted white birch, trembling aspen, and balsam poplar are scattered throughout. Balsam fir is absent. Most of this vast area is Precambrian Shield, but south and west of Great Bear Lake the section extends onto Palaeozoic and Cretaceous sediments. Large and small lakes occupy a high percentage of the surface area. The Lower Mackenzie region includes upland subarctic black spruce woodland dissected by white spruce forests on well-drained, coarse-textured river bottom soils, and willow-alder forests on fine-textured bottomland soils. Alaska birch tends to replace trembling aspen and balsam poplar on uplands sites, and tamarack is absent. There is far more nonforested than forested land. The Forest-Tundra section occupies a narrow band extending from the Mackenzie delta, along the southwwestern and southeastern coasts of Hudson Bay, and across northern Quebec to the Atlantic coast of Labrador. It is the northernmost portion of Canada with tree cover. Stunted forest patches occur mostly along shores of lakes and rivers, with tundra barrens in the uplands. The tree line has fluctuated widely since deglaciation, with evidence for a recent retreat over much of the area. White spruce occurs mostly in areas with a maritime influence, and black spruce and tamarack are dominant in the interior. Pine is absent; balsam fir and boreal hardwoods are very infrequent. The Alpine Forest-Tundra section occurs to the west of the Mackenzie lowlands, with open, park-like stands of stunted white spruce occurring on mountain slopes to an elevation of about 1200 metres. Alpine fir is often found at treeline on northern and eastern slopes. Alaska birch and black spruce are mixed with white spruce on lower slopes.

3. Alaska

The treeline in Alaska, defined as the limit of conifer tree species, extends along the south side of the Brooks Range, reaches to Bering Sea at Kotzebue and Norton Sound, dips sharply to the south to the Bristol Bay coast, and crosses the Alaska Peninsula to Kodiak Island (Viereck 1979). Each mountain range in Alaska also has its own treeline, from near sea level in western Alaska to an elevation of nearly 1250 m in the eastern interior. Over such a large and diverse area, one would expect the treeline to be influenced or controlled by several factors.

The transition from boreal forest to arctic tundra is usually gradual, occurring over a broad transitional area. Several authors, especially Hustich (1966) and Hare and Ritchie (1972), have described and defined a number of forest tree limits in this transition from forest to tundra. Some of these boundaries, proceeding from forest to tundra, are (Viereck 1979): (1) economic forest line, where productivity is 1.5 m^2 or more per year and regeneration is reliable; (2) forest line where tree cover is continuous; (3) the limit of trees, where trees are above the snow and 2 to 5 m in height: and (4) species line or limit of a tree species, whether in tree form or not, the "treeline" of Hare & Ritchie (1972).

There is a great deal of difficulty in defining distinct vegetation zones in Alaska. The complex physiographic patterns, the presence of permafrost, the fire-vegetation relationships, and the oceanic influence along the western coast have prevented the establishment of a south to north zonation of vegetation types similar to those described for Canada, Scandinavia, and Russia. In like manner, the concepts of several treelines and forest lines and a forest-tundra zone are not easily applied in Alaska. As Hare and Ritchie (1972) pointed out, the presence of high mountain barriers at precisely the point where one would expect to find the northern treeline is one of the reason that zonal vegetation does not occur at the forest-tundra boundary. Both the Alaska Range and the Brooks Range break the general north-south trend of climatic zones and create a continental climatic centered on interior Alaska in the Tanana and Yukon basins. It is possible to map a mosaic of vegetation types, but it is impossible to separate these into distinct vegetation zones (Viereck 1979).

A second factor complicating treeline and zonation in Alaska is the series of river system, which expands the closed forest environment to the west and southwest. Well-developed forests are found on the flood plains of the Kobuk, Yukon, and Kuskokwin Rivers in areas where the

surrounding uplands are treeless. The active flood plain presents a permafrost-free substrate where trees grow rapidly and reach commercial size; whereas the older terraces and uplands may be closely underlain by permafrost and support a few scattered trees, or they may be completely treeless (Viereck 1979).

4. Russia

Timberline forests in Russia are called as *pretundra forests*. Also, in English text the term near-tundra forests has been used. The term "pretundra forest" (Pritundravye lesa, the direct translation means forests close to the tundra) has been used in the Russian literature on forests since 1940's. However the breadth, geography, borders and geobotanical nature of the pretundra forests are still being discussed. These forests have an important environmental and stabilizing role. They are distributed from Norway to the Bering Straits and vary remarkably in vegetation pattern. These forests include patchy forest stands, which are found from tundra region, whole forest-tundra and also the northernmost part of taiga (Certovskoj et. al 1987). This area is about 45 million hectares, and about 47% of it are forests.

The criteria for pretundra forests have been defined with the help of climatic, landscape-ecological and silvicultural parameters that are used in the zonation of forest vegetation in Russia (Semenov & Ogibin 1998). A protection belt, with strict regulations on the use of nature, was established in the northern part of the pretundra forests by a decree of the Russian government in 1959, but the borders of the pretundra forests zone have not been defined as a whole. However, this protection belt exists and it extends to 100-150 km to the south of the northern timberline (Kaitala 1997, World Bank...1997). The question concerning the southern boundary of their area extent is still open, since no uniform fundamental criteria have been established for identifying pretundra forests (Abaimov & Sofronov 1996).

Extending along latitudinal belts from north to south, forests are: pretundra (a transitional zone from tundra to taiga or coniferous forests), taiga (subdivided in northern, middle, and southern zones), broad leaved forest zone, and forest-steppes (transition from forests to steppes). Pretundra forests are part of the Group I forests, with boundaries that define a conventional management unit. These boundaries do not coincide with those of the forest-tundra zone, which is a unit of geographical division of the territory. Work is currently under way to mark out the boundaries of the boreal zone. Pretundra forests encompass a 100-150 kilometer-wide belt of vegetation that forms a latitudinal

transition from taiga forests to tundra. Reindeer pastures in the Russian north are found in these forests, along with rich fishing grounds and considerable reserves of valuable nonwood forest products. These forests are rarely dense. Single-storied stands of simple structure prevail, with few tree species (one- and two-species stands are most common). In general, as one moves north and east, forest lands become more scarce, species composition is less diverse, stands have a more open canopy, diameters of trees decrease, and trees often have stem deformities. The dominant species are larch (Larix gmelini, L. sibirica), spruce (Picea obovata), birch (Betula cajanderi), and dwarf Siberian pine (Pinus Pumila).

Permafrost forests constitute a special environmental protection issue. Half the forested areas in Siberia and Far East are in permafrost areas, which are very sensitive to natural and anthropogenic disturbances. Permafrost conditions create land surface instability from frost heave and subsidence and present challenging management issues, regeneration problems (mortality, leaning trees), and infrastructure concerns (roads breakup more easily under permafrost conditions). Since 1959 a special protection zone has been established to shield the northern pre-tundra forests from commercial exploitation. Based on extensive research in permafrost areas and on a model of the northern region, the Sukachev Forest Institute has proposed moving the strict protection zone further south, which would greatly increase protection of some of the most fragile landscape in Siberia and Far East. The proposed line is shown on map IBRD 27086R which is published in the World Banks Book of Russia's Forest (see literature).

5. Finland

The northern timberline forests in Finland are desired into three major regions as follows: (1) The northern protection forest zone where forestry activities are restricted (suojametsäalue), (2) forests at high altitudes (korkeiden alueiden metsät) and (3) the Inari commercial forest region. The *Protection Forest Act* (*suojametsälaki*) was adopted in 1922, with the aim of preventing degradation of northern forests and to prevent the forest line from declining due to human impact (Veijola 1998b). The southern limit of this forest region goes to where the effective temperature sum is about 700 d.d. The forest region was determined by using climatic records, and because they were not complete in 1922, the Inari region was left out of the protection region although the effective temperature sum is around 700 d.d (Vormisto 1995, Kankaanpää & Vormisto 1998). Forests at high altitudes are described as, forests which are lying higher than 250-330 m above sea

level and have been considered unsuitable for timber production on an extensive scale due to the difficulties in applying normal regeneration practices. The land area in forest protection zone is 3 150 000 hectares, and 95 % of it is owned by state. The amount of productive forest land inside this zone is 800 000 hectares. The areas of protective timberline forests are marked on maps and on field in Finland (Veijola 1998b).

Today, the new forest act issued in 1996 replaces the old 1922 Protection Forest Act. This new act states that, "The Council of State may designate areas as protection forest areas where preservation of the forest is necessary to prevent retreat of the timberline. In protection forest areas, the forest shall be managed and utilised with special care and in such a way that the measures do not result in retreat of the timberline. The Council of State may issue necessary general regulations about the forest management and use in protection forest areas. Before the government decision concerning a protection forest area is taken, the forest owners, relevant municipalities and other authorities are to be heard. In addtion negotiations shall be held with the Sami Parliament."

Felling a tree stand in a protection forest area for purposes other than domestic use shall be permitted only in accordance with a felling and regeneration plan approved by The Forestry Centre of Lapland. If the special local conditions so require, the ministry responsible for forestry matters may also restrict the removal of wood for domestic use of prohibit it completely.

6. Norway

The definition of *mountain forest* (*vernskogen*), or forest close to timberline, is not very exact. In particular, the lower border causes difficulties whereas the common definitions of the uppermost borders are clearer in Norway. The treeline is drawn where scattered trees have a height of 2 m, while the timberline is where the maximum distance between trees is 30 m and minimum tree height 3 m (Mork & Heiberg 1937). The upper limit of what is defined as a productive forest is somewhat below the timberline. A productive forest should have a mean annual yield potential of at least 1 m^3 per hectare. A general characteristic of mountain forest is that in such forest temperature is a strong limitation for both forest yield and tree reproduction. Forest close to the timberline usually has low stand density and trees per hectare of the same size and age, but the common feature is variation (Nilsen & Haveraaen 1982).

Mork (1958) roughly estimated the average horizontal width of the mountain forest in Norway to be 500 m. By using figures for the length of the timberline, estimated by Norges Geografiske Oppmåling to be 47 000 km, we end up with nearly 2.5 million hectares, or about 1/3 of the total forest area in Norway. The current timberline is sometimes lower than the climatic timberline. For instance, local mountain farming, with browsing domestic animals and heavy cutting of firewood, may temporarily lower the timberline.

In the high mountain area in southeastern Norway the climatic coniferous timberline is over 1000 m a.s.l. Generally the height of the timberline varies considerably from south to north, From the interior to the coast, and even from the central part of southern Norway to the east (Abrahamsen et al. 1977). Hence, to relate the lower limit of mountain forest to a certain height above sea level has no meaning. According to Børset (1986), some researchers have used 60-70% of the height of the timberline as the lower limit of the mountain forest. Bergan (1974) has on the basis of climatic studies, suggested relating the lower limit to a vertical height difference from the climatic timberline. This vertical belt could then be valid all over the country. This means that under unfavorable conditions, as in the far north, all forests should ecologically be classified as mountain forest (Haveraaen 1995).

For the forest close to the timberline the Norwegian forest law has for a long time contained a particular paragraph about cutting regulations. In every district of the country an imaginary line is drawn some vertical distance below the timberline, often 100-200 m. Above this line the forest owner can only cut dead trees without special permission. If forest owner requests more cutting, the national forest service must carry out the marking. This regulation was stated long time ago, when mountain farming and heavy cutting were real threat to the future of the mountain forests (Haveraaen 1995).

Mountain birch is the dominating tree species in the upper belt close to the timberline in the western part of Fennoscandia. Mixed with the birch we find groups or single trees of aspen (Populus tremula), gray alder (Alnus incana), mountain ash (Sorbus aucuparia) and bird cherry (Prunus padus). All these species have a temperature demand for the four summer months of about 7.5 °C, while spruce (Picea abies) and pine (Pinus sylvestris) require about 8.4 °C. The difference between the mentioned broad-leaved trees and the conifers means a vertical altitude difference of 100-150 m. A change in the average summer temperature of 0.6 °C (June-September) is equal to an altitude difference of about 100 m. Thus, on steep slopes the belt of broad-leaved trees is quite narrow,

while on nearly flat ground, it will dominate large areas. Birch also occurs quite frequently in the upper coniferous belt. In the most arid mountain regions, pines form the coniferous timberline. However, since humidity dominates the Norwegian climate, spruce is the most common conifer (Haveraaen 1995).

The ecological balance in the forest close to the timberline is very unstable. Treatments carried out in a climatically good period may lead to success, while the same treatments under less favorable conditions can result in a complete failure. In much of the mountain forest top and stem breakage caused by heavy load of snow and sometimes aven ice occurs frequently. The wind often adds additional restrictions both summer and winter. Wind in summer reduces the maximum temperature within and close to the needles and leaves. Strong wind can also damage the needles physically in winter by snow and ice drift and by drying in both summer and winter (Haveraaen 1995)

7. Sweden

Sub-montane forests (*fjällnära skogar*) form a continuous belt along the chain of mountains which stretch from the province of Dalecarlia to northern Lapland (Vormisto 1995). The border is based on so called forest cultivation line (skogsodlingsgräns) which was set at the beginning of 1950s by the Forest Service (Domänverket). The border was re-established in 1991 by the Swedish Government and extended to also include private land. The regeneration capacity and the profitability of forest management decreases above the forest cultivation line. The law defines sub-montane as, "forests with difficulties in regeneration and which are above the forest cultivation line according to forest inventories". The entire alpine region covers an area of about 9 million hectares, of which 1.5 million hectares are productive timberland (Kankaanpää & Vormisto 1998).

8. Iceland

There is a good report on forests in Iceland in this proceeding made by Thorbergur H. Jónsson. In Iceland all forests may be defined as timberline forests. The decrease of forest area in Iceland show clearly how sensitive timberline forests are to human impact. Birch forests (with rowan and aspen in some areas) are the only native forests in Iceland. Native birch forests have suffered from massive deforestation since the settlement of the country in about 870. The afforestation requires a lot of effort (fencing and protection) due to erosion and sheep grazing. The importance of forests as a wind protection is clearly seen in Iceland.

Also, the tree and shrub cover has an important protective and stabilizes effect on the soil. Native birch, lodgepole pine and Siberian larch are mainly used in afforestation programs. The forest land area is increasing because of the succeeded afforestation programs.

9. Greenland

The distribution of the three Greenland "trees": the European Betula pubescens and the American Sorbus groenlandica and Alnus crispa especially towards their N limit clearly reflect their preferring the interior with mean July temperature at ca. 10 °C against ca. 6 °C at the coast (Fredskild & Ødum 1990). Low forests of Betula pubescens with Sorbus groenlandica and Salix glauca are found in protected valleys in the interior.

The Norse landnam in S Greenland, just before A. D. 1000, drastically changed the nature: grazing of sheep, goats, cattle and horses, tree cutting for fuel and timber, peeling of sods for house building, etc. reduced tree growth, broke the thin vegetation cover (Fredskild 1978, 1988) and caused soil erosion in those areas most exposed to the foehn winds (Jacobsen & Jacobsen 1986). However, after 4-5 centuries of utilization of the land, the Norsemen's gradually leaving the stage, resulted in recovery of the forest, at least locally. In recent centuries, the local population of man has been cutting fjords, by which it could be sailed to the settlements, leaving remote valleys less exploited (Oldendow 1935). In 1930, the most well-known forest clad valley, Qingua-dalen, was protected (Fredskild & Ødum 1990).

The introduction of sheep-breading, at the beginning of this century, once again locally changed the vegetation severely, and whereas Salix glauca can stand biting to a certain degree, no regrowth of Betula pubescens is found where even a few sheep are grazing. Some of the most vulnerable birch forest areas are now being protected by fencing (Fredskild & Ødum 1990).

10. The autumnal moth and grazing in mountain birch forests in Fennoscandia

Reflecting the combined effects of climate and history, the treeline area of northwestern Fennoscandia (see the map in Kankaanpää & Vormisto 1998) is occupied by continuos and almost pure mountain birch, Betula pubescens Ehrhart ssp. tortuosa (Ledebour) Nyman = *Betula pubescens ssp. czerepanovii (Orlova) Hämet-Ahti, forests*

(Oksanen et al.1995). North (or in high elevation areas) of the coniferous forests, mountain birch is the prevailing species. Climatically, the mountain birch forests of northern Fennoscandian are heterogeneous, stretching from continental inland plateau with low precipitation, thin snow cover, cold winters and at least discontinous permafrost, to coastal mountains with copious snowfall and mild winters (Ahti et al. 1968, Hämet-Ahti 1963, Tuhkanen 1980, 1984, Haapasaari 1988, Kullman 1989, Oksanen & Virtanen 1995). This area is also culturally heterogeneous, being a part of four different countries with disparable possibilities and policies for sheep and cattle raising and reindeer husbandry. Grazing, climate and edaphic factors interact to shape the current mountain birch forests and woodland in northernmost Fennoscandia. Sizes and forms of individual birches seem to primarily depend on moisture. Even the composition ot the tree layer seems to depend on moisture. In climatically, or edaphically moist sites, a substantial part of the tree layer consists of tall willows, and also rowans are present. Conversely, treeline woodlands of dry inland areas are normally monocultures of mountain birch, except for occassional aspen clones (Kallio & Mäkinen 1975), and scattered, stunted pines (Kallio et al. 1971, Oksanen 1995).

Mountain birch forests are periodically defoliated by the autumnal moth, Epirrita =*Oporinia autumnata (Borkahausen)*. Epirrita outbreaks are restricted to northern and mountainous regions of northwestern Europe, but the range of both moth and birch cover much larger areas (Haukioja et al. 1988, Oksanen et al. 1995). Normally the birches can recover from 1-2 years of defoliation but sometimes forests can be killed over large areas, e.g. in Finnnish Lapland in 1965-1966 (Kallio & Lehtonen 1973). The critical temperature for the survival of eggs of autumnal moths is -36° C. This together with the geographical and topographical distribution of minimum winter temperatures causes clear patterns in the distribution of damage during outbreaks. Defoliation is more common in the upper parts of slopes while forests in the valley bottoms are protected by ´cold air lakes´ (Kallio & Lehtonen 1973, Tenow 1975, Niemelä et al. 1987, Haukioja et al. 1988, Neuvonen et al. 1998). It is more common for defoliated trees to recover after defoliation, but still drastic changes may occur in the ground cover as grasses and herbs increase and flower more frequently (Oksanen et al. 1995). These changes may cause long-term effects in the functioning of the ecosystem (both terrestrial and aquatic) and in human activities (e.g., grouse hunting and reindeer husbundry, the traditional way of land use).

Conversely, the structure of mountain birch forests is mainly determined by grazing. In areas without substantial summer grazing by

either sheep or reindeer, the birch forest grades into a scrubland and the position of the timberline depends on how the concepts 'tree' and 'shrub' are defined. Whatever definition on prefers, there is no distinction between the tree line and the forest line. Although there is a transitional zone, where patches of forest occur in topographically and edaphically favorable sites (along creeks, on south-facing slopes), while treeless heaths and scrublands occupy unfavorable sites (depressions, ridges, north slopes). There is a broad zone of open woodlands, and the uppermost woodlands are savanna-like, with scattered, large trees growing here and there in an otherwise open landscape (Oksanen et al. 1995).

Reindeer are limited by a relatively unproductive resource, the lichens on winter range, and thus probably cannot persist at such high densities as to have equally strong impacts on the regeneration of birches as the sheep have on the Atlantic coast. Also behavioural differences are likely to contribute to the difference in the impacts of sheep and reindeer. Sheep are truly domestic animals and graze freely in woodlands and forests. Reindeer, in turn, avoid forests in the summer, due to the mosquito problem (Itkonen 1948, Skjenneberg & Slagsvold 1968) and a perceived risk of predation (Henshaw 1970, Helle et al. 1990). On the other hand, leaves of mountain birches are preferred food items in early summer (Skjenneberg & Slagsvold 1968). Thus, there is a positive feedback loop, where decreasing abundance of birches leads to increasing intensity of reindeer grazing on the remaining ones. This mechanism becomes especially potent if it is combined with strong outbreaks of E. autumnata, forcing birches to regenerate from basal shoots (Oksanen et al. 1995).

Reindeer is a native ungulate of northern Fennoscandia and has been present in the area throughout the post-glacial period. It is unlikely that predators could regulate reindeer numbers at levels lower than the meagre carrying capacity of hemiarctic ranges (Kelsall 1968, Caughley 1976, Oksanen 1988, Crête et al. 1990, Crête & Huot 1994, Messier 1994). Morover the interaction between Epirrita and reindeer probably occurred in ancient times as well. We are thus inclined to regard the existence of open woodlands in the vicinity of the treeline of northern Fennoscandia as the truly natural situation (Oksanen et al. 1995).

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The role of the tourism in the northern timberline forests

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Tourism, world-wide, is growing at a phenomenal rate - between 5 - 10% per annum. Over 520 million people travel annually, generating 3.4 trillion USD in gross output, nearly 11 percent of the world's gross domestic product and employing over 200 million people. This makes the travel and tourism industry the largest in the world and every region is affected - including the Arctic.

This major growth in tourism is a fairly recent phenomenon and results from improvement in transportation systems, decreased costs for travel and increased access to even the most remote regions of the world.

However, tourism is a two-edged sword - along with the phenomenal benefits, especially economic, there is a very real downside. All too often, those benefits are not shared and only a handful of people reap the economic rewards. Furthermore, these same people are often non-residents. Other problems are oversaturation and deterioration of sites, transportation bottlenecks, overwhelmed cultures, or growing resentment in many local communities and business.

The travel and tourism industry has not been immune to these problems and the World Tourism Organization, the World Travel and Tourism Council and the Earth Council banded together and recently developed an "*Agenda 21 for the Travel and Tourism Industry*" which focuses on the sustainability of tourism in an environmentally compatible manner. In that document, the industry acknowledges that with its very powerful economic role world-wide, the industry "has a moral

responsibility to take the lead in making the transition to sustainable development".

The industry has laid out the following principles for sustainable tourism:

- *travel and tourism should assist people in leading healthy and productive lives in harmony with nature*
- *travel and tourism should contribute to the conservation, protection and restoration of the Earth's ecosystems*
- *travel and tourism should be based upon sustainable patterns of production and consumption*
- *travel and tourism should recognise and support the identify, culture and interests of indigenous peoples*
- *environmental protection should be an integral part of the tourism development process*
- *concerned citizens should be participants in tourism development*
- *local populations should adopt tourism planning decisions*

The industry, therefore, has recognised its responsibilities towards the environment and local communities. It recognises the serious damage that unfettered tourism development has unleashed and is striving to improve the situation. It also realises that this makes very good business sense since, like any other business, tourism is subject to market forces and can be buoyant or depressed.

And, like other industries, a main challenge for the tourism industry is to maintain a steady, growing demand for its products. This means it must build a client base, satisfy its clients expectations and needs, and foster repeat and attract new business. In the Arctic, this is not always easy.

The arctic region - A specialised, niche market

The Arctic is a relative new-comer in the field of tourist attractions. For centuries, and to some extent today, the Arctic is viewed as a cold, desolate frozen expanse devoid of all but a few native people and polar

bears. Consequently, attracting people to the Arctic for tourism is more difficult than for many other regions. Not only do attitudes need to be shifted and tourist expectations met, but facilities to accommodate tourists have to be put in place. A major goal for all the Arctic countries and many northern communities, therefore, is how to build a sustainable tourism industry that can contribute to overall sustainable development.

It goes without saying that without tourists, there is no tourism industry. The first question, therefore, is "what attracts tourists to the Arctic"? The main answer is "nature". Arctic tourism is predominantly nature-based, either consumptive (e.g. hunting and fishing) or non-consumptive (cultural and ecological, often termed "ecotourism"). In short, the main tourism appeal of the Arctic is its wilderness, its unique cultures, its fish and wildlife and its pristine, majestic land- and seascapes.

Most people visiting the Arctic have very specific expectations, including:

- unspoiled and unscarred nature
- serenity
- the opportunity to commune with the natural environment
- new experiences
- the opportunity to learn about the environment and cultures of the north

At the same time, however, unless they are what are termed "adventure tourists" intent on braving the elements, tourists to the Arctic also want a reasonable amount of "creature comforts". In other words, hotels, well-kept campsites, clean water, stores to purchase supplies and local artifacts, reliable transportation. And they would like these provided with minimal and discrete human intervention of the natural environment. Given the interesting mix of expectations, it is little wonder that Arctic cruises and chalet visits are very popular and growing forms of tourism. Both provide the opportunity for nature tourism along with the security of a comfortable "home base".

Tourists are demanding and if their expectations are not met, they will not return. Equally ruinous for the industry, and many local communities dependent on tourism, they will spread that message and deter other potential visitors.

The Arctic tourism market is small relative to other parts of the world. Tourism industry officials refer to it as a specialised "niche"

market. One of the reasons is the very fact that it is primarily nature-based and nature-based tourism, world-wide, accounts for only about 7% of all tourism. Whereas there are over 500 million tourists world-wide, Arctic tourists number only a few thousand spread over a region millions of square kilometres.

Suitable tourism destinations in the Arctic are quite limited. For instance, despite its massive size, much of the Arctic is not suitable or accessible for tourism either because of climate, desolation or inaccessibility. Those things that attract tourists and the tourism industry tend to be concentrated in specific locations, many of which contain designated "protected areas" because of their biological diversity and pristine natural landscapes and seascapes. They are preferred destinations for both tourists and tour operators.

Retaining and building the tourism market

Because the Arctic tourism market is small and specialised it is very vulnerable to shifts in demand. In parts of the Arctic, such as Greenland, the industry is still very much in the development and growth stage. In others, such as in the Yukon and in parts of Alaska and Scandinavia, it is already a major pillar of the economy. To retain the industry that already exists and to develop tourism in other parts, it is extremely important that the tourists that come to the Arctic return to their homes with a positive outlook. Over time, this will not happen if their expectations are repeatedly curtailed.

Some of the major things that will deter tourists are over-pricing and high costs, poor accommodations, unfriendly hosts, inadequate transportation along with anything that takes away from the primary motive for the visit in the first place, i.e. the enjoyment of nature. Some specifics that deter tourists include:

- unplanned development that spoils a natural setting
- inappropriate human intervention or structures
- noise of machinery
- scarred landscapes
- sights or activities that jar

Things that attract most tourists are:

- accommodation that is suitable for the site
- infrastructure that blends in

- tranquil setting
- reliable service and food
- unscarred landscapes

The role of arctic tourism

The entire Arctic economy does not, and cannot, rely on tourism. It can be a major short and long-term income and employment source for local communities and serve to profile Arctic cultures. Nevertheless, it is only one of many industries in the Arctic and must co-exist with them. One of those industries is forestry which also contributes heavily to the economic fabric of the north.

Too often, however, the forestry industry and the tourism industry find themselves in a conflict situation. Activity inherent in forestry (i.e. felling, machinery noise etc) are abhorrent to the many tourists who come to the Arctic to "escape" the industrial activity which surrounds them in the south. They have come to relish the pristine majesty of the north - not to be confronted with a patchwork of scarred, clear-cut landscapes and logging roads.

Nevertheless, the two must co-exist somehow even if, on the surface, they are mutually incompatible. The issue must become one of accommodation rather than mutual exclusion. How do you retain and foster a tourism industry while promoting other forms of industrial activity, such as forestry?

There are several ways and all rely on good planning and co-operation between the tourism industry, other industrial sectors and local communities.

For example, during the planning process, it is important to appreciate that tourism is more than just the visit but is a cultural experience that begins far in advance of the visitation itself and relies to a great extent on built-up expectations. Industry can help shape that expectation. For example, it can educate the potential tourist by providing information on the economic reality of the north and by explaining that in some areas, activity such as mining and forestry extraction are important components of the economy and are contributing to sustainable economic development. Some primarily nature-based tourists find this sort of dialogue very informative and would be interested in touring industrial operations.

Another way to accommodate the two types of industry is to keep them apart. This is a successful strategy that is already taking place in many locales. Tourism using parks or other protected-areas as destinations is an effective way to implement such a strategy since these areas have usually been set aside for their biodiversity, natural beauty or cultural value.

Another point is that to ensure that all forms of development are compatible, and that the benefits of tourism accrue not only to the industry but also to local inhabitants, there should be clear guidelines on site usage and community involvement, accepted by the industry, governments and communities.

Finally, it is in everyone's best interests to maintain as natural an environment as possible since, as stated at the outset, this is what draws the majority of visitors to the Arctic. Furthermore, it is now an undeniable and basic economic fact that some entire communities are becoming heavily dependent on the tourism market or are planning to be since it has the potential to provide widespread, ongoing employment opportunities and economic benefits, if properly planned and managed.

END

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Timberline research in Finland

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Concepts

The timberline and its surroundings form an *ecotone*. This is a transition zone between two ecosystems. A timberline ecotone is characterised by a wider biodiversity than that in either of the ecosystems adjoining the area. In timberline research the main objects of interest are the ecotones lying between the closed canopy forests and treeless highland (rock tundra). The forests near the timberline, especially the protected forest zone in northern Lapland, are also research targets.

The concepts *timberline* and *treeline* are commonly used in Finland. They are misleading in some respect because it is not a question of a real line. The alpine timberline of the fells is in fact very distinct, and at the same time forms the treeline. It is usually more difficult to locate the arctic timberline because it is a transition zone varying in breadth between a closed canopy forest and treeless highland. In Russia and in some North American research communities the concept *forest tundra* is used to describe the area lying between the *boreal taiga* and *tundra*. This concept is not appropriate here because there is no actual permafrost tundra in Finland and the transition zone between the forest and treeless area is not as wide as in Russia, Canada or Alaska. There are few treeless areas in Finland; they are restricted to the fells and treeless highland located more than 500 meters above sea level where the mountain birch does not grow. The timberlines and treelines in Lapland have both an arctic and an alpine nature, in other words they are regulated by the ecological factors typical of high altitudes and arctic climate.

The purpose of timberline research

The timberline is one of the most sensitive indicators of global climate change. It has been forecasted that the mean temperature of the growing period will increase by 3 – 4 °C during the next few decades. This would mean that the seed years of conifers will increase in frequency and the timberlines will move towards the north and up the slopes of the mountains. The timberline ecotones give us much useful information for determining the nature and speed of climate change. Such information will also be needed in the future, e. g. in preparing for the effects of the global change.

The sensitive nature of the timberline ecotone means that it is easily damaged by man's activities. In Finnish Lapland and the neighbouring countries there are several competing forms of land use. A considerable amount of ecological knowledge is needed in planning and controlling land use. Information is also required for integrating tourism, forestry, reindeer husbandry and other natural sources of livelihood . The methods used in silviculture and timber harvesting in the protected forest zone in northern Lapland and in other forests near the timberline are primarily based on the results of practical research. Information on timberline ecotones is also needed for the planning and decision-making of nature protection. During the last few years a number of broad international programmes have been started to ensure the sustainability of natural resources in the arctic areas. These programmes also need some fresh information to support them.

In the timberline areas the trees are growing at the extreme limits of their distribution. Properties and features that are not apparent in areas with better growing conditions can be identified and measured in such areas. The timberline ecotone offers a versatile environment to study the diversity, physiology and genetics of trees.

The Finnish Forest Research Institute (METLA) and the Finnish Forest and Park Service have carried out a large number of afforestation experiments in timberline forests and on the northern side of the timberline since the beginning of this century. Some experiments have also been made with exotic tree species, usually from Siberia or North America, since the 1980s. These experiments provide useful information for the afforestation of the wide treeless areas of the globe (e. g. in Iceland, the Faeroe Islands and mountain areas in the developing countries).

Timberline research in the Finnish Forest Research Institute (METLA)

The main part of the timberline research is included in the project **"The ecology and use of timberline areas"** organized by Kolari Research Station in co-operation with Rovaniemi Research Station and several domestic and foreign universities. The project was started in 1994. The main points of a new action plan for the years 1999 - 2003 are presented here.

The research project is aiming at:

- producing basic ecological knowledge about the timberline ecotone and the forests near the timberline
- producing knowledge and action alternatives for the management and land use planning of the timberline areas and the forests near the timberline

The project consists of three subprojects (see also Fig.1 in appendix):

1. Basic research of the timberline ecotone
2. Regeneration, growth and tree species dynamics in timberline forests
3. Management and protection of timberline areas

The objectives and contents of the subprojects and the partners co-operating with METLA are presented in the following:

1. Basic research of the timberline ecotone

1.1 The location and changes in timberlines and the factors regulating them

The exact locations of timberlines and treelines are defined in co-operation with The Northern Lapland District for Wilderness Management of the Finnish Forest and Park Service. The northern timberlines of Scots pine, Norway spruce and mountain birch forests are defined using aerial photographs and field data. The field survey of the pine treeline is being performed using a GIS application. The project "Northern Lapland Nature Survey" of the the Finnish Forest and Park Service has just finished the nature mapping of the key biotopes. This data will be used for a natural resources plan that replaces the former forest management plan. A large amount of spatially referenced data, which are available for the timberline research, have been collected in connection with the planning work. The material contains information

about forest stands e. g. the growing stocks, surface vegetation and soil. A book called "*The Nature of Northern Lapland - Biotope Atlas*", based on the material of the nature mapping is going to be published and commercially distributed. The project will participate in its production. The results of the mapping will also be presented in the publications of this project.

A *vegetation mapping* has been implemented in the Pallas - Ounastunturi National Park with the aid of GIS. The location of the alpine timberline can also be seen on this map. Precise field measurements are made, in particular to determine the local annual temperature sum. These measurements are supplemented by data recorded at the weather stations of the Meteorological Institute of Finland at Pallastunturi and in the nearby areas. In the southern parts of the Pallas - Ounastunturi National Park damage caused by the crown snow load also affects the location of the alpine spruce timberline. The significance of the crown snow load and its connection with climatic factors and possible changes in these are studied at Sammaltunturi. The equipment used to measure the crown snow load has been developed at the University of Oulu. The data are combined with meteorological observations from the Sammaltunturi weather station. The result of this experiment is a *model of crown snow accumulation.*

The timberline monitoring project was started in 1983 / 84. The study plots were established in 12 areas (Fig. 1), and remeasured in 1994 / 95. The third round of measurements will be made during the last year of this project, in 2003. The main objective of the project is to follow possible shifts in the timberlines and treelines of different tree species, and to follow changes in the regeneration and growth of forest stands. Tree damage and the species composition and coverage of the ground vegetation are also followed on these study plots. The Kolari and Rovaniemi research stations and the northern field stations of the Universities of Helsinki, Oulu and Turku are participating in this work.

The ecological factors behind changes in the timberlines and treelines are being studied with the help of the following:

- the weather stations built in 1997 - 1998 at the northern treeline of Scots pine (*Pinus sylvestris*)
- the measurement data collected by the stations of the Meteorological Institute of Finland and METLA
- soil moisture measurements

The weather stations measure the air and soil temperatures, wind direction and speed, rainfall, air humidity and solar radiation. Cluster plots with a 2 km radius have been established around the weather stations. The trees and seedlings are measured and site information collected on the plots. The information from the weather stations and the response variables of the study plots are used to construct models to clarify how the ecological factors affect the development of treelines and timberlines.

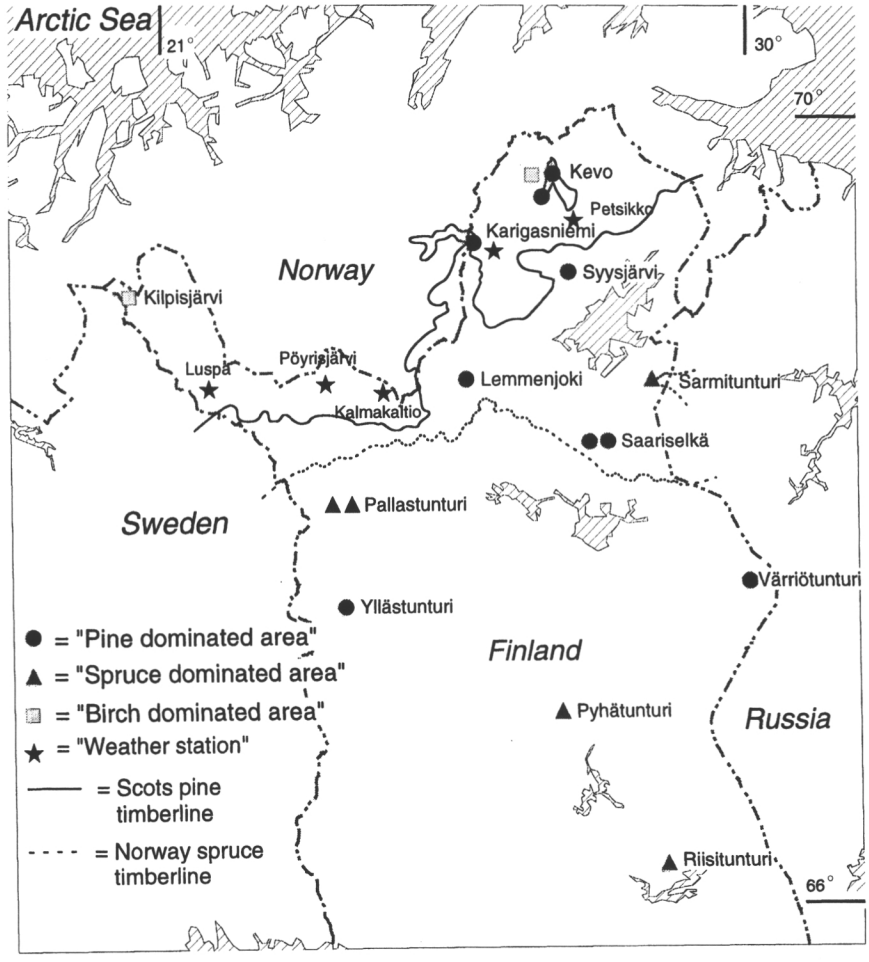

Figure 1. Location of the weather stations and the study areas of the Timberline monitoring project.

The natural regeneration and growth of pine stands are the most important dependent variables. The collection of weather and climatic data is done in co-operation with the Meteorological Institute and researchers at the Geography Department of the University of Oulu. The subproject studying soil moisture and its effect on the timberline is carried out in co-operation with the Regional Office for Northern Finland of the Geological Survey of Finland.

1.2 Biodiversity

The biodiversity of timberline forests is studied in co-operation with researches from the Arctic Centre (University of Lapland). Experiments on the species composition of beetle fauna and fungi in timberline forests are being carried out. The influence of forest management methods in these forests is also studied. A new study has been started on the rate of decay of different tree species and the factors affecting it in natural conditions in the forests near the timberline.

Regional ecological planning has been started in both the private and state forests. The most important aim of the planning is to maintain biodiversity. Special emphasis is placed on saving *ecological corridors* and *key biotopes* from felling and forest management in general, and on leaving decayed wood in the forest in order to maintain biodiversity. So far, these measures do not have any theoretical basis derived from domestic studies. In order to correct this situation, a study will be carried out in the forests near the timberline on the ecological principles of regional ecological planning. It will generate basic information and instructions for the management of the timberline forests.

The most important research targets are:

- the grounds for regional ecological planning: to create know-how about marking the key biotopes and ecological corridors
- to produce research information as a basis of the measures with which diversity is to be maintained (e. g. the amount of decayed wood, reserve trees in clear cut areas)

2. The regeneration, growth and dynamics of the timberline forests

2.1 Natural regeneration

In the timberline forests the most important factor for the regeneration of conifers is the maturing of seed and adequate seed development in order to ensure the stocking with seedlings. On the average, there have been three good conifer seed years so far this century. It is expected that the warming of the climate will considerably increase their frequency. Mountain birch (*Betula pubescens* ssp. *czerepanovii*) mainly regenerates vegetatively.

Regeneration and its ecological factors are being studied with the help of field surveys and laboratory experiments. Timberline researchers in Finland have always been the most interested in Scots pine. Several long term experiments on the succession of natural and artificial regeneration of pine are being followed. Climate chamber experiments have recently been started in co-operation with the University of Joensuu. The effect of temperature and other climate factors on the development of conifer seed is being studied. The seed study also includes X - ray analysis and germinability analysis. The regeneration of Norway spruce is being studied on the northern spruce timberline after regeneration felling. Comparative experiments have been started in natural forests near the regeneration areas.

The main objective in these experiments is to develop models that describe the preconditions for the regeneration of pine and spruce. A considerable amount of information on climate and soil is also needed for these models. This information is obtained from the weather stations and the soil moisture measurements mentioned earlier.

2.2 Tree species experiments

The METLA, a number of universities and the Finnish Forest and Park Service have some old study plots where both domestic and exotic tree species and their provenances are being tested in timberline conditions The most important tree species being tested in these experiments are: Scots pine *(Pinus sylvestris)*, lodgepole pine *(Pinus contorta)*, Norway spruce *(Picea abies)*, white spruce *(Picea glauca)*,

black spruce *(Picea mariana)*, Siberian larch *(Larix sibirica)* and tamarack *(Larix laricina)*.

2.3 The growth of timberline forests

The growth of timberline forests has so far not been studied very much. Information is needed, among other things, for preparing instructions for the management of the forests near the timberline and for following and predicting the effect of climate change.

Dendrochronological research methods (the analysis of annual growth rings) have produced new, comprehensive information on the growth and development of timberline forests in Lapland during the last 7600 years. The dendrochronology laboratory at the Rovaniemi Research Station can produce accurate growth analyses for different time periods. These analyses are a good basis for predicting the effects of climate change on the timberlines and treelines.

The radial growth of trees is also measured on the permanent study plots by means of girth bands. Accurate information is obtained about the growth variation during the growing season and the start and end of the annual growth. Annual *height* growth is also measured on the same study plots. Growth models for timberline trees can be constructed using these growth measurements and ecological information from the weather stations. These models explain the magnitude, timing and variation of growth. The growth models are used e.g. in drawing up forest management instructions for the areas near the timberline.

2.4 Forest damage

The METLA and the Kevo Subartic Research Institute (University of Turku) are starting an experiment on *the use of GIS (Geographical Information System) for predicting forest damage in timberline areas.* Methods for estimating the risks of insect pest and fungal epidemics are being developed.

Seedling damage caused by reindeer, moose and other mammals and their effect on the regeneration of conifers in timberline forests is being studied on fenced study plots. The effect of reindeer on the regeneration

of timberline forests has been found to be significant, especially in the areas where the number of reindeer exceeds the carrying capacity.

So called *winter desiccation*, which is one of the most severe abiotic stresses along the alpine timberlines of Central Europe and North America, also occurs in Finland. This phenomenon seems to be more complex than earlier studies have indicated. Seasonal variation in the hardiness of timberline trees against frost and winter desiccation in areas with different temperature and light conditions are being studied. The tests will mainly be performed in late winter when all possible abiotic stress factors are affecting the trees at the same time. The effects of UV radiation and altitude on winter desiccation are also being studied. In addition, the variation in winter desiccation in different parts of the forest and in different kinds of timberline forest (with varying tree species, site etc.) are also being studied.

2.4 Tree species dynamics

The METLA is participating in a *Nordic mountain birch research project.* The ecology of mountain birch and its adaptation to climate change are being studied. In Finland these studies are carried out in the Pallastunturi and Kilpisjärvi areas.

Because of the high economic value of Scots pine, it has been regenerated naturally and even planted on the northern limit of its distribution area, as well as to the north of this boundary. It was realised in connection with this regeneration work that one of the most important factors controlling the northern treeline of pine is the competition between mountain birch and pine. Although there are currently no plans for expanding the area of pine forests, it is worthwhile studying this competition for ecological reasons. In this study, the influence of climate, soil, insect pests and fungi on the success and growth of these tree species are being elucidated.

3. The management and protection of timberline areas

3.1 Silviculture

Silviculture has to be carried out carefully in the protected forest zone of northern Lapland and in other forests near the timberline. The Finnish Forest and Park Service and some private forestry organizations have their own instructions for these areas, but there is no solid theoretical basis behind these instructions. Pressure from nature protection organizations has resulted considerable changes in felling work and in silvicultural methods, although the suitability of the new methods has not been studied. In forests in Lapland traditional felling has largely been replaced by "landscape fellings", in which the traditional border between intermediate fellings and regeneration fellings is not as clear as before. *Regional ecological planning*, which has been introduced in the state forests, is largely based on foreign research. Against this background it is necessary to start to study the management methods for forests near the timberline.

The silvicultural research in the timberline forests includes the following topics:

1. Forest regeneration
2. Stand cultivation
3. Landscape fellings
4. Prevention of forest damage
5. Application of regional ecological knowledge to silviculture

The silvicultural research in this project focuses on the forests near the timberline, especially on the protected forest zone and the fell highlands. The study will be carried out in close co-operation with the Finnish Forest and Park Service and the organizations of private forestry, in order to ensure that the results can be put into practice as efficiently and as rapidly as possible. The METLA and the Finnish Forest and Park Service have joint regeneration experiments, that will be used in this study.

3.2 Land-use planning in timberline areas

There are several forms of land use in timberline areas that also partly compete with each other (forestry, tourism, reindeer husbandry, picking berries, fishing, hunting, the building of roads etc.). A large number of organizations and interested parties participate in the land-use planning and decision-making. The project is offering research information for the use of planners and decision-makers and acts as an expert in problematic situations.

3.3 Nature protection in timberline forests

Several reports and statements have been requested for a number of domestic and Nordic publications and reports from the researchers of the project by the Ministry of the Environment, the Finnish Environment Institute and the Lapland Regional Environment Centre.

Several programmes and reports concerning the protection and condition of the environment in the circumpolar arctic are about to be initiated. The project will also offer expert help in the future.

A co-operation project with the Northern Research Institute of Forestry in Archangel (N-W Russia) has been planned. In this project the southern border of the forest tundra protection belt in the Archangel and Komi regions will be updated. The commercial cuts carried out in the taiga zone will soon reach the forest tundra zone. Local researchers are of the opinion that the protection belt that was defined in the late 1950's does not extend as far to the south as it should. The aim of this project is to clarify in detail the ecological and biological basis for defining the southern border of the Archangel - Komi protection forest belt. Funding from the EU, the Nordic Council or some other source is needed for carrying out this project.

International and domestic co-operation

During its first five years the timberline research project has found several partners in research communities and universities in other Nordic countries, Northern Russia, Canada, the United States and Germany. The

joint projects and publications, seminars and exchange of students have been the most important forms of co-operation.

The following points provide possibilities for developing international connections and co-operation on timberline research in the future:

- resources are increasingly aimed at the use of natural resources, nature protection and the sustainable use of natural resources in the circumpolar arctic by the EU and countries in North America.

- Finland co-operates to a considerable extent with countries in the Barents area and acts as a leading country in the project on biodiversity protection in the area. This project also concerns the northern timberline in North-West Russia. Finland is also involved in research on the protection of the environment and sustainable development carried out by the Arctic Council. In this project Finland has actively brought up the timberline theme.

Domestic co-operation is also important. During the last five years the project has succeeded in forming an "umbrella" over the small units and individual researchers who have earlier worked alone. Joint applications for funding, studies and publications, the development of communications and efficient planning of the use of resources with other organizations are the main forms of co-operation.

Other projects

In addition to the research project presented above, there are several other projects run by METLA, Finnish universities and other research organizations. Some most interesting projects are mentioned in the following:

- University of Helsinki, Department of Geology: *Dendrochronology and climatic history (especially Holocene environmental and climatic changes) in the tree-line area of northern Fennoscandia*
- University of Joensuu, Department of Forest Ecology: *The influence of the climate change on timberline and treeline development*
- University of Oulu, Department of Geography: *Plant geography of high latitudes, climatology of alpine timberlines in Lapland*

- University of Turku, Kevo Subarctic Research Institute: *Long-term environmental monitoring at timberline; The effects of pollutants on subarctic forest ecosystems*
- The Finnish Meteorological Institute: *Measurement stations of Arctic Monitoring and Assesment Programme (AMAP) and Global Atmospheric Watch (GAW) in Pallas-Ounastunturi National Park*
- METLA, Rovaniemi Research Station: *UV-radiation and the plants at the timberline*
- METLA, Rovaniemi Research Station & several European universities and research organizations: *Forest response to Environmental Stress at Timberlines (FOREST): Sensitivity of Northern, Alpine and Mediterranean forest limits to climate*

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Sustainable use of northern timberline forests in Iceland

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Birch (*Betula pubescens*) woods and shrub cover about 125.000 hectares in Iceland (1.3% of the land area) and are found from sea level to 300-550 meters altitude (Bjarnason et al. 1977, Kristinsson 1992). Sub-Arctic birch woodlands and shrub are the only indigenous woodland types in Iceland and the whole of the lowlands may be defined as being within the timberline ecotone.

More than 2,8 million hectares (28% of the land area) are within the climatic species limit of *B. pubescens* and up to 20% of the land area may have been grown with birch woods or shrub before the settlement of the country in about 870 AD. The difference being edaphicly unsuitable areas such as wetlands and recent lava fields at that time and areas of frequent and catastrophic disturbance such as glaciofluvial outwash plains exposed to catastrophic floods due to sub-glacial volcanic eruptions or sudden draining of glacial lakes.

About 80% of the present woodland area is covered by shrubby birch less than 2 meter tall. The birch forms only low shrubs (1-2 meters) in regions with extreme oceanic climate and heavy coastal storms (Kristinsson 1995), but shrubby birch also dominates climatically favourable as well as marginal landscapes. Decades of exclusion of grazing animals and wood cutting has rarely resulted in increased stature of the shrubs. Hence much of the lowland areas are apparently beyond the maritime- and edapic- treelines of birch defined as trees of 2 meters or more in height.

In more sheltered and edaphicly favourable sites inland with a climate tending toward continentality birch may reach 8-13 meters (Kristinsson 1995, Sigurðsson 1977, Bragason 1995). However only

1,7% (2.200 hectares) of the birch woods are with taller trees than 8 m (Bjarnason et. al. 1977, Sigurðsson 1977).

The concept of treeline defined, as the limit to which woody plants attain a specified reference height, is of doubtful meaning in Iceland. The variation in tree stature is continuous from prostrate shrubs to trees of more than 13 m in height. None of the suggested reference heights for treelines (2-5 meters) seem to demarcate any important phytogeographical discontinuity. The species limit of Birch, on the other hand, appears to broadly coincide with the demarcation between the Temperate, and the Alpine and Arctic elements in flora and fauna.

The experience from planting exotic species from North America in birch shrub has shown that a number of species are able to attain more than 5 meters height in 20-40 years. These include among others Sitka spruce (*Picea sitchensis*), lodgepole pine (*Pinus contorta*) and black cottonwood (*Populus trichocarpa*). Lodgepole pine is apparently able to grow to tree size within most of the species range of native birch in Iceland. It is a prolific seed producer on most sites, from the age of 20-30 years, and healthy vigorous seedlings are frequently found around pine plantations. Hence most of the birch shrub is within the potential treeline of a number of boreal tree species.

Species composition in native birch woods

Birch is almost the only tree species present in native woodlands. However rowan (*Sorbus aquiparia*) and aspen (*Populus tremula*) are occasionally found among the birches. Rowan is locally common in birch woodlands in some fjords in North West Iceland but is rare in other parts of the country. The rowan trees are usually 3-5 meters tall and frequently extend 1-2 meters above the canopy of the birch shrub. On favourable sites rowan may attain the height of 10-12 meters and the stature is on those sites similar to that of birch.

Native aspen is only found at eleven sites in North East Iceland. It is a prostrate shrub except in the woods of Egilsstaðir, where trees up to 8 meters in height are found (Sigurðsson et al. 1995).

Salix phylicifolia and *S. lanata* are common shrubs in birch woodlands and may form willow shrubs throughout the lowlands. On moist sites *S. phylicifolia* occasionally forms a small polycormic tree up to 5-6 meter high but is generally a shrub of no more than 1 meter in height. *S. lanata* is of lower stature rarely exceeding 2-2,5 meters but is

generally 1 meter or less (Kristinsson 1995). Prostrate juniper (*Juniperus communis*) is found in some woods.

Regeneration

The birch regenerates almost exclusively by basal stem sprouts, but extends its range by seed. Seed production is generally prolific throughout the country. Seedlings are rarely found within continuous birch woodland but frequently at woodland edges.

Aspen, rowan and willows in birch woods also regenerate vegetatively by root sprouts or basal stem sprouts. Seed production in native aspen has never been observed and the species exists by continuous replacement of older stems by root sprouts (Benedikz 1994). Rowan flowers and sets viable seed. Willows are prolific seed producers and seedlings generally appear in abundance on suitable sites following the exclusion of grazing animals.

The native birch woods have suffered massive deforestation since the settlement of the country in about 870 AD, primarily due to clearing of the woods for pasture and hay fields, overgrazing, and overexploitation for firewood and charcoal. Locally, and to a lesser extent, volcanic eruptions, catastrophic floods in glacial rivers and glacial advance during the Little Ice Age has contributed to the deforestation.

Massive soil erosion has followed the deforestation. Erosion by wind and water almost complately removes the whole soil profile and has left extensive barren deserts of sand, gravel or lava fields.

The freely drained soil is inherently unstable and tree and shrub cover has an important protective and stabilizing effect on the soil. It is mainly Andosol formed by aeolian deposition of volcanic tephra, and palagonite loess from the central highlands and as well from eroding soils.

The Andosols are able to accumulate high quantities of carbon due to fixation in complexes of organic material and amorphous clay minerals. The erosion of the Andosols leaves land vith very low carbon content. However by reestablishing vegetation cover the eroded areas may be able to capture considerable quantities of carbon dioxide from the atmosphere. Reforestation and revegetation programmes have been included in Iceland's strategy to limit emissions of green house gases and

enhance removals from the atmosphere by sinks of carbon dioxide (Anonymous 1995).

Forestry

The first successful forestry programme was initiated in 1899 under the supervision of Danish foresters. In 1907 the State Forestry Service was established and it took over the Danish initiative. The main emphasis of the forestry service until the 1930s was regulation of harvesting and protection of the native wood resource. Continuous cover sylviculture with selective felling was introduced and clear cutting, winter grazing of domestic animals, and clearing of forests was banned.

Afforestation

Afforestation programmes were started in the 18th century, however unsuccessfully until the 20th century. Planting was on a small scale until the 1950s. From then to 1990 the annual planting rate was about 0,5-1,0 million trees per annum. Since 1990 the annual planting rate has been 4-5 million trees per annum (about 1000 hectares per annum). In 1995 three species accounted for 76% of the planting effort, native birch, lodgepole pine and siberian larch (*Larix sukaczewii*), 21,1, 26,4 and 27,9% respectively. Over thirty species accounted for the remaining planting (Pétursson 1996).

Timber harvesting is only on a very small scale and mostly firewood. During the last 50 years the annual cut in the birch woods has been about 200 tonnes per annum. In the first half of the 20th century the annual cut was 1-2 thousand tonnes per annum (Anonymous 1997). Timber harvesting during the 20th century is very small compared to annual growth rate of 102.000 tonnes per annum (0,82 tonnes per hectare per annum) (Jónsson, unpublished data). However before the 1870s the birch woods were intensively exploited for charcoal production and firewood. Harvesting is as yet very limited in conifer plantations and it is only round wood from early thinnings.

Threats to biodiversity in native birch woods and shrub

Grazing of livestock, sheep in particular, has been the main threat to the existing birch woods and the principal obstacle to expansion of native woodlands. Grazing pressure is declining and there is a trend towards exclusion of free- range grazing from increasing areas. Hence grazing will probably be less important for the existence of native birch woodlands in the future.

The main threat in the future will probably be invasion of exotic tree species, conversion to conifer plantations, and development for recreation.

From the 1950s to the 1970s the plantation effort was concentrated on converting native birch woodland and shrub to plantations of exotic conifers for timber production. Birch woods were heavily thinned and planted with conifers. In the 1970s these practices were largely abandoned and since then plantations have almost exclusively been established on treeless landscapes. However large areas of native birch are in the process of conversion to monocultures of exotic conifers with great loss of biodiversity as the stands reach pole stage and shade out most of the native flora. Unfortunately the underplanting effort was concentrated in the very rare high forests with birch 8-13 meters tall. Hence a policy of removing the exotic plantations from these woods is urgently needed. Furthermore a policy of controlling the introduction and spread of exotic species is urgently needed for Iceland.

Birch woods and shrub is in demand for holiday homes and recreation. Considerable areas have been developed for these purposes particularly close to centres of population. In these areas there are high densities of cottages, roads and paths, and exotic tree species are planted among the birch. The exotics generally grow to considerably greater size and shade out the birch and native ground flora as they mature. Some are prolific seed producers and are able to agressively invade the birch. Hence much of this area will with time be converted to an anthropogenic environment dominated by exotic species. With increasing prosperity and declining demand for grazing the development of native birch woods for recreation use is perceived to increase.

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The importance of timberline habitat for caribou in north America

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The timberline habitat of North America, comprised predominately of the species *Tsuga mertensiana* and *Chamaecyparis nootkatensis* at the upper timberline (north of 42° N) and aspen (*Populus tremuloides)* and other species of the genera *Picea, Abies, Pinus* and *Larix* forming other timberlines (Holtmeier 1996), is believed to be an important habitat for some large herbivores, such as caribou.

It has been documented that caribou populations use this particular habitat type as it serves a variety of different functions for this species. It may be a vital habitat component that is required by the animal rather than one that is merely utilized.

The combination of larger, older trees adjacent to more open stands (described as the climax *Krummholz* spruce and fir community) has shown to be important as an early and late winter habitat of the caribou. In North America and Southern Canada, most southerly populations of caribou feed on arboreal lichen while the larger northern-most herds feed predominantly on terrestrial lichen. However, the woodland caribou *Rangifer tarandus caribou*, an endangered species in some US states and Canadian provinces, use the timberline habitat for various functions throughout the year.

The predominant function of this habitat is that of a feeding area during the early winter, whereby caribou can forage on the rich supply of arboreal lichens and evergreen shrubs that are usually found in this habitat type (Bergerud 1972). Studies incorporating winter field trials in Northeastern Washington, found that caribou fed from live sub alpine fir (*Abies lasiocarpa*), standing dead snags and windblown trees, all of

which are predominant sources of arboreal lichens (Rominger et al 1996).

Lichens (*Ascomycetes*) are eaten by most ungulates in North America. However none of these ungulates are as dependent on lichens as the woodland caribou in ecosystems of western North America, where deep snow precludes cratering for terrestrial forage. In northeastern Washington and Northern Idaho for example, Selkirk woodland caribou descend from the higher elevation summer habitat (in sub alpine fir and Engelmann spruce (*Picea engelmannii*) forests) to use stands of western red cedar (*Thuja plicata*)/western hemlock (*Tsuga heterophylla*) and the ecotone between these two communities, during early winter. As snowpacks deepen and harden, caribou reascend back up to the late winter habitat, to a niche unoccupied by other ungulates, where they feed on a monophagous diet of alectoroid arboreal lichens in the relatively open stands of sub alpine fir and Engelmann spruce (Rominger et al 1996). Sub alpine fir dominates the windthrow component at sites used by caribou and may be the reason why caribou used higher elevation habitats (Rominger 1989).

The arboreal lichens are a satisfactory substitute for the unobtainable terrestrial lichens, becoming the most available forage, and therefore the primary food item above the snow cover in both boreal and mountainous environments (Rettie et al. 1997, Bergerud 1972). However it must also be stated that arboreal lichens are utilized by caribou during all other seasons throughout the year (except spring) and may therefore be a simple indicator of caribou requirements for trees old enough to support the slow growing epiphyte (Servheen et al. 1989).

In addition to the rich supply of arboreal lichens, overall forage, including terrestrial lichens and ground level shrubs are most abundant in areas where forest and tundra meet. Here the scattered trees protect the shrubs and lichens from exposure but are not sufficiently dense enough to seriously reduce light required by the lower strata (Bergerud 1971).

For a rich supply of arboreal lichens to exist however, timber stands must be substantially older than traditional harvest rotation lengths. Arboreal lichen biomass increases with stand age, and peak biomass generally is not attained until stands are older than typical 100-120 year timber harvest rotations (Rominger et al 1996).

This old growth occurrence within the forest is usually found at higher altitudes, that is, at the timberline level where timber extraction and management are often very difficult or economically impractical. In North America, many remote timberlines have not been disturbed at all,

or they have been disturbed relatively little by humans (Holtmeier 1996), and thus they offer a great possibility for old growth forest to exist. This yet again substantiates the fact that the relationship between old growth timberline forests, lichens and caribou is critical and hence the need for preservation of this habitat type.

Quebec, an area also dominated by Northern boreal timberline forest extending to the northern forest tundra, is another region of great importance for woodland caribou. Studies conducted in this area reveal that lichens are of primary importance for these animals in winter and make up 50-75% of their diet (Scotter 1967). The two main caribou herds in Quebec (the George and the Leaf river's herd) that comprise close to one million individuals, feed primarily on terrestrial lichen. Overgrazing is thus currently being observed in calving areas due to the high abundance of individuals.

The availability of the arboreal lichen forage is very dependent on the age of the forest stand. The mature forests of the upper mountainous and subalpine vegetation belt in Quebec are characterized by mature fir/spruce, with these forest types supporting the highest arboreal lichen biomass (Arseneau et al. 1997). In contrast, both the immature stands, at lower elevations and the alpine tundra habitat demonstrate a low abundance of arboreal lichens (Quellet et al. 1996). Also, in Gaspé Provincial park in Quebec, logging is prohibited due to the importance of the mature forests for caribou and the problems of regeneration at these high elevations. Also because of the slow growing nature of arboreal lichens, this forage would not be available to caribou for at least several decades should logging activity occur (Hale 1983). From other studies conducted in Quebec it could be seen that there is a definite trend between high lichen removal by caribou in late successional stands and hence the clear preference for winter use of mature and sub mature forests (Arseneault et al 1997). These studies in Quebec also recorded that many of the summer locations of the caribou were in fact located in the areas used in the winter period, i.e. the older age, higher elevation stands. It may therefore be the case that the timberline area is not only important as winter habitat but as an important habitat, which is utilized all year by the caribou.

Studies in Newfoundland have shown similar evidence to the importance of old age timberline forest stands for arboreal lichen forage for caribou. One study discussed that if the timberline zone, termed the subalpine zone, was destroyed by fire for example, the absence of a tree stratum will likely prevent caribou from using this range (Bergerud 1971). This is not only because of the lack of forest shelter but due to the immediate removal of lichen biomass which will take many years, if

ever, to return. In some cases the replacement of the tree line forest with barren tundra will create a drier microclimate less favorable to lichens (Klein 1982).

Another important function of the timberline habitat for the woodland caribou is for the purpose of bedding sites within small openings (Rominger et al 1996). These openings are often a feature of the ecotone timberline type (transitional belt), whereby a mosaic of islands of trees and open meadows occurs throughout the transitional habitat, between the alpine belt and the closed forest (Holtmeier 1996).

Calving habitats utilized by pregnant caribou have also been identified, these being predominantly low basal area stands which are open canopied, having a high density of lichens, reasonably high elevation and a low road density. The occurrence of the open areas and small trees at these relatively high elevation sites may be chosen to avoid areas with high predator populations and maximize calf survival (Bergerud et al 1984). Even though there was no literature directly stating that timberline habitats are used for calving areas, timberline habitats generally show these characteristic.

A similar picture as to the use of timberline forest by woodland caribou in the lower 48 states of America and the lower provinces of Canada can also be seen with regard to the barren-ground caribou (*Rangifer tarandus granti)* in the Northwest Territories of Canada and Alaska.

Scientific literature from these areas also considers lichens to be the most important, if not the sole source of winter food for caribou on most continental ranges (Scotter 1967). Similarly, to the previously stated examples in the lower parts of Canada and the America, lichens are often dominated by species characteristic of old growth coniferous forest belts, which are the predominant range of the barren-ground caribou (Scotter 1967). They are of high energy value and the native grazers are specifically adapted physiologically to use them (Klein 1970). However, due to the slow growing nature of this group of plants, they are a consequently a very precious resource for the caribou in these regions.

However studies conducted on the Seward Peninsula of Alaska have shown that lichens grow more rapidly in open forest than on the treeless tundra (Pegau 1968). This is probably due to the moister microclimate of the timberline, compared to the drier microclimate of the tundra, resulting in favorable conditions for lichen growth (Klein 1982). This indicates therefore that the timberline would be a favorable place for

caribou grazing, due to the likelihood of a higher lichen abundance as opposed to in the higher tundra habitat.

The loss of arboreal lichens as forage and the loss of the timberline habitat overall, due to fires or logging, is a matter of concern, especially when it involves small isolated woodland caribou populations on limited ranges (Van Daele 1983). Early winter habitat requirements of woodland caribou conflict with clear-cut logging operations, and because of the importance of dead subalpine fir in the windthrow component, forest management should incorporate both the prevention of the removal of standing dead trees and the preservation of such old growth habitats (Rominger et al 1989). This is being conducted in central Saskatchewan where both the government and the forest industry have identified woodland caribou as a species whose preservation will affect forest management in this province (Rock 1992).

In view of the high dependence of most large mainland American barren-ground caribou herds, and the smaller endangered populations of woodland caribou on lichens as the primary component of their winter diet, it seems obvious that any activity that destroys a significant portion of lichen range will have potential long term, detrimental consequences for the caribou (Klein 1982). Therefore the preservation of the timberline habitat and hence the invaluable lichen forage must be protected in view of the very important old growth timberline forest, arborial lichen, and caribou relationship.

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The effect of reindeer on soil nitrogen and carbon dynamics

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Reindeer grazing has altered the plant community composition in northern boreal forests and in tundra ecosystems (Väre et al. 1995, Oksanen and Virtanen 1995) which changes the amount and type of carbon and nitrogen available for soil microbes. Nutrient cycling is extremely dependent on chemical composition of decomposing matter, and by affecting the vegetation grazing has an indirect effect on decomposition processes and plant nutrition (Pastor et al. 1992, 1993). In the nutrient deficient, lichen dominated vegetation types, grazing increases the proportion of more decomposable litter types and may enhance nitrogen cycling. The summer diet of reindeer gives a competitive advantage to species producing slowly decomposing litter. Thus, in the boreal ecosystems, reindeer grazing can have a positive effect on nutrient cycling in unproductive vegetation types and a negative effect in productive vegetation types. Combined effects of litter quality and soil microenvironment on nutrient cycling are complex, and for predicting the effect of reindeer grazing on soil, not enough information is available. The aim of my studies is to determine the effect of reindeer grazing on nitrogen cycling in northern-boreal and oroarctic ecosystems at different levels of primary productivity.

We will measure the gross and net mineralization of nitrogen (Hart et al. 1994), release of carbon (Nordgren 1988) and the size of microbial carbon and nitrogen pool (Anderson and Domsch 1978, Brookes et al. 1985).The effects of chemical quality of litter and soil microenvironment on the decomposition will be separated by transplant experiments.

In an oligotrophic lichen dominated site in Kätkäsuvanto, grazing had decreased the microbial biomass, release of C and gross mineralization of N, but increased net mineralization (Stark 1998). Thus, reindeer grazing had affected the ratio of inorganic C and N released by soil microorganisms. The reason for this is probably decreased immobilization of N by soil microbes during organic matter decomposition, which

is caused by a lack of energy for microbes. In Reisduottar, northern Norway, all microbial parametres indicate more rapid organic matter turnover in the summer pasture (Olofsson et al., 1999). There was an equal amount of microbial C in the summer and winter pasture, but mineralization and soil respiration were higher in the summer pasture.

There are clear indications, that reindeer grazing causes changes in the soil processes in northern ecosystems. The soil processes are essential for ecosystem function, and interact with the productivity of the ecosystem. The changes in soil processes can also explain some of the physiological changes in forest trees. The investigations will be applied on ecosystems at different levels of productivity to get a wide outlook on the long-term effect of reindeer on forest productivity.

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The threats to the traditional sami livelihood in timberline forests in Finnish upper Lapland

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The northernmost province of Finland, Lapland, is a good area to observe a traditional indigenous way of life and its relationships to modern, economical forms of land use. Lapland covers about 30% of Finland's land area, but in the circumpolar arctic perspective it is a relatively small area. In Lapland we can find several of the problems that concern or will concern people living in northern timberline forests around the circumpolar region. The Sami homeland area, Sapmi, includes the three northernmost provincial municipalities of Finland (Inari, Enontekiö and Utsjoki) and the northernmost reindeer-herding district, the Lapin Paliskunta of Sodankylä provincial municipality. The area is characterised by coniferous forests, mountain birch woodland and open tundra fells. Sami are obviously people of timberline forests.The situation contains elements for a conflict in interests between traditional livelihoods and modern business, and there is considerable public discussion at the present time on this toac. Reindeer herding, hunting, fishing and berry-picking represent tradition, while forestry, mining, energy production, tourism and nature conservation represent modernity. A similar kind of controversy has occurred throughout the northern timberline forests whenever the modern way of utilizing natural resources has started in such areas. This article discusses contemporary Samiforms of livelihood in timberline forests and how they manage within the modern concept of economic markets.

The Sami people are well adapted to the natural conditions in which they live.They can be classified into several groups in terms of livelihood and geography (Nickul K. 1970). The prior to 2nd world war there were Sami of the coniferous forests and Lake Inari, mountain Sami and river Sami, Sami of the coast and Sami of the Kola Peninsula.

The Sami who lived in coniferous forest made a living by fishing, hunting and small-scale reindeer herding. In the spring time the families, called baiki, moved separately from the winter villages to their summer regions. These lappvillages and the areas they lived in were called Sida. Sidas were essential, because the people received their livelihood from nature. The storehouses were said to be more important than the dwellings. People lived in small timber cabins and, depending on the season, in tents, lean-toes and in natural shelters by a fire.

The Mountain Sami started to live off reindeer herding after the wild deer disappeared as a result of overhunting, and the full nomadic way of life began in the Swedish mountains in the 17th century. It spread rapidly througmout northern Scandinavia. The importance of fishing and hunting has been marginal for the Mountain Sami. At the end of winter, the seasonal migration took place over long distances from forest areas to the coast of the Arctic Ocean. The full nomadic way of life was subjected to considerable pressure after political agreements on borders were drawn up between the unified states. In practice, the period of extensive reindeer herding lasted up until the 19th century, and ended in 1852 when Russia closed the border with Norway. In 1854 Norway denied reindeer herders the right to cross the border. The seasonal micration became shorter and Mountain Sami reindeer herders also started to move down into southern areas.

It has been said that the Sami culture in Finland, as we understand it today, was more authentic in the 1930's than before or after this time (Lehtola T. 1997). Subsistence living flourished in Eastern Lapland, and a rich reindeer nomadism in western Lapland. The Sami culture was strong and cultural exchange between the Sami and the Finns were of benefit to both parties. At the end of the 2nd World War, the Finnish Army fought against German troops in northern Finland. The population was evacuated from Lapland to central parts of Finland and to Sweden. After the war, much of the infrastructure in Lapland was destroyed and rebuilding in the area brought a lot of new people up to the north. A strong wave of modernization and assimilation started. The snowmobile was invented in the 1960' s and the traditional way of life underwent significant changes. At the beginning of the 1970's the so-called Sami renaissance and a strong Sami movement for indigenous rights started (Lehtola V-P. 1994).

Today the traditional Sami livelihood has adapted to the technological innovations of the modern world. Reindeer herding, hunting, fishing and berry-picking are occupations practiced by many

Sami and local non-Sami people. It s also an important hobby for people engaged in some other profession in the Sami homeland area. For the Sami the question of their traditional livelihood is culturally and politically very important. In Finland, problems concerning the legislation of aboriginal land-use rights have not yet been solved. The Sami people want to develop a traditional livelihood from their own base in order to ensure that the tradition is continued in a modern fashion. The modern industry and administration established by outside parties has caused problems between traditional and modern ways of making one's living.

Forestry

Forestry research started in Lapland already in the 1860´s. The disadvantages of unplanned, intensive forestry were recognised and legislation was needed. The new law to protect the forests of Lapland was enacted already in 1922. In 1939 the State Council passed a decision concerning the protection of the northern timberline forest area, which included the Petsamo, Utsjoki and Enontekiö municipalities and parts of other municipalities in Lapland. The forest resources of Lapland were utilised extensively to improve Finland's economy after the 2nd Wold War , but modern intensive forestry did not come to Upper Lapland until the 1970's.

For a traditional livelihood intensive forestry meant a decrease in the amount of forest areas available for subsistence living and multiple use. Clearcutting and deep plowing of forest land destroyed huge areas of reindeer grazing. These areas have not recovered in 30 years. Forestry also meant the construction of roads for timber transportation, which opened up access for other activities and brought more people to the areas. Above all, the wilderness regions become fragmented and this had negative effects on ecology in the region.

Power production

Houses and shelters were headet by wood before the 2nd Word War and subsequently up until the 1980's. Firewood collection had only small-scale effects on timberline forests. Fire was also used for cooking and illumination. When firewood became too scarce in one place, the

families started to look for a new place to live in. The traditional way of life had no damaging effects on timberline forests.

Two large artificial lakes, the Lokka and Porttipahta reservoirs, were constructed at Vuotso in the northern part of Sodankylä municipality in the late 1960`s. Water covered more than 630 000 ha of living and grazing areas and completely changed reindeer herding in the area (Massa 1994). Reindeer had to find new routes and many of them were drowned when trying to walk on floading peat islands. Fishing was an important secondary occupation for the local reindeer herders but, because of the artificial lake, the nature of fishing and the catches become uncertain.

Wind power plants are a relatively new and ecological form of energy production, but it has indirect effects on the traditional Sami livelihood, e.g. construction, new roads and other form of infrastructure. Telecommunication masts, electricity power lines and similar kinds of construction disturb nature in the wilderness areas. Fragmented wilderness areas have a negative impact on traditional forms of livelihood.

Mining and mineral exploration

In Upper Lapland, large-scale mining and mineral exploration started in the Petsamo area after nickel had been found, and large mines were opened in the 1930`s. Finland lost the Petsamo area to the Soviet Union in the 2nd Wold War and, when the war was over, most of the Skolt Sami from the area moved to Finland. Petsamo is still important mining area in the Russian Murmansk Oblast. Gold has been the most important metal mined in Lapland. Gold mining has been practiced on a relatively small scale in Upper Lapland. There are some areas where machines are used, and the river water has become temporarily muddy. As long as the parent lode of Lapland gold is not found, and as long as contemporary technology cannot exploit the small deposits profitably, there is no threat to traditional livelihoods. However, exploration is still going on and technology is improving. Fortunately for the traditional livelihood, there are no gas or oil deposits in Finnish Lapland.

As a combative way of land use, mining has far reaching effects. Depending on the technology which is used, mining and mineral exploration destroys the surface of the land, makes noise and requires infrasructucture. Pollution of the surrounding areas decreases the

lichenstands, the most important food for reindeer, and makes it impossible to practice other traditional livelihoods belonging to Sami culture close to the mining industry.

Tourism

Tourism became popular in Finland in the 1930's. Mountain skiing, an open port to the Arctic Ocean at Petsamo, and northern exoticism were the trademarks of tourism in Lapland. Rebuilding brought new roads to Upper Lapland after the end on the war. Tourism became more and more popular and it created new economical possibilities. Today tourism is one of the most important sources of livelihood in Upper Lapland.

As a competitive form of land use, unplanned tourism can have negative effects on the traditional Sami livelihood. For example, construction of the Saariselkä tourist center in Inari municipality in the 1970's split a traditional reindeer herding area into pieces. Calving can be disturbed in spring by skiing tourists, dogsledges and snowmobiles. Mass tourism shares the same activities as the local people practice for a livelihood. Near roads and tourist centers fishing, hunting and barry-picking can hardly be an occupation because of the sparse natural resources .

Nature conservation

Nature conservation can be both a supportive and competitive form of land use for the Sami livelihood and culture. The idea that indigenous people are a part of nature has spread globally. The way in which indigenous people have traditionally used land to gain a living has been seen as sustainable use and accepted as a part of nature. The traditional indigenous culture is bound to nature: what happens to the land happens to the people. However there is also a considerable amount of controversy among modern world conservationists (Järvinen A. 1994). From their point of view, indigenous rights are acceptable only if the indigenous people practice their livelihood in the sustainable way.

The effects of the Sami livelihoods may have negative effects on the ecological balance: In the Sami way of life there are two matters which produce negative reactions among conservationists. They are both

associated with reindeer herding: overgrazing and the hatred shown towards predators. The problem is the number of reindeer. Competitive land use has reduced the size of grazing areas, and traditional grazing ground rotations have become difficult. It is also difficult to get enough profit from reindeer herding because new forms of technology, such as snowmobiles, four wheeled drive vehicles, cars, motorboats and motorcycles are very expensive to buy and run. Also there is relatively little understanding for killing predators in the western culture. The number of reindeer is ecologically debatable, since the cause of the situation lies elsewhere.

The Sami Parliament approved The Sami Program for Sustainable Development in March 1998. The aims of the program: to develop the Samis' influence in decision-making concerning their own area, livelihood and culture, to ensure the vitality of the Sami culture in advantageous interaction with other cultures and the sustainable use of nature resources in the Sami homeland area by adapting the livelihood activities and recreation use of nature to the bearing capacity of nature.

Contemporary development

In conclusion there are some recent elements that can be seen as supportive of the traditional Sami livelihood. The State Committee Report of Wilderness Areas, KM 39/1988, was published in 1988. It included the principle that the Sami culture and the traditional Sami livelihood are an integral part of the wilderness areas, and they should be protected by multiple and sustainable use of the wilderness. In the Act on Wilderness Reserves, no. 62/1991, the aim was to preserve wild areas, to safeguard the Lapp culture and indigenous livelihoods, and to develop a potential for the diversified use of nature.

The National Board of Forestry has been appointed the supervising officialbody for the wilderness areas. The wilderness areas belong to the state in the contemporary legislation. The Sami people consider that landownership has never been legally transferred from the Sami to the State. Political discussion is going on; who has legal rights to the areas owned by the state in Upper Lapland, and how to define who is a Sami.

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Recent dynamics of white spruce treeline forests across Alaska in relation to climate

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Introduction

Treeline is the dynamic boundary between forest and other, lower-statured vegetation, usually tundra or grassland. The position of the tree limit at any given time reflects both the factors that limit tree growth at present (e.g. temperature, moisture) and longer term historical events and conditions which have limited tree growth in the past (Sirois 1992). As a result, to understand the treeline of today it is helpful to know both the current relationship of trees to their environment and some of the major tree-limiting events of the past, including the recent past. Predictions

about future changes in treeline will be greatly aided by a clear understanding of these issues as well (Starfield and Chapin 1996).

There are several reasons to believe that the late 20th century is an unusual period of climate and ecosystem change, and that the Alaska treeline should reflect these changes. Data from lake sediments, trees, glaciers, and marine sediments are in general agreement that the Arctic climate warmed from about 1840, the end if the Little Ice Age, to the mid 20th century to a nearly unprecedented degree (Grove 1988, Overpeck et al. 1997). Since 1976 a strong warming has dominated the Alaska climate, and a variety of effects of climate change have appeared in Alaska forests (Juday et al. 1998). Since the mid to late 20th century radial growth of high latitude and high altitude trees at the forest/tundra margin across the entire northern hemisphere has become less sensitive to warmth (Briffa 1998).

In this paper we look at trends in recent (20th century or mid-20th century and later) climate factors associated with treeline at widely separated locations in Alaska. We present some data from some recent treeline investigations and from the major locations where treeline is being monitored on a long-term basis in Alaska. Finally, we suggest what near-term future changes might be expected in the Alaska treeline.

Synopsis of Alaska vegetation history

At their maximum extent Pleistocene ice sheets covered about half of Alaska, primarily in the coastal south and southcentral regions and the Brooks Range and Alaska Range mountains. The interior of Alaska formed a continuous unglaciated zone across the Bering Land Bridge into the Eurasian continent. Prior to 14,000 14C yr BP, interior Alaska was treeless and sparsely vegetated in general. One reconstruction of this environment suggests it was an arctic steppe supporting large herbivores (Guthrie 1990). Another school of thought suggests the vegetation at this time was a barren, unproductive tundra (Ritchie 1982, Cwynar 1982). Pollen studies provide some evidence that late Pleistocene vegetation of interior Alaska most closely resembled the modern herb-rich sparse tundra vegetation of high Arctic islands of Canada.

Between 14,000 and 12,000 14C yr BP vegetation cover of interior Alaska changed dramatically following a sudden and sustained climate warming. *Betula*, most probably the shrub species *B. glandulosa* or *B. nana*, suddenly appeared in abundance across much of the landscape. Most herbaceous taxa from the prior colder period remained in the newly warmed landscape which was thought to be a patchy mosaic of birch on mesic sights and herbaceous taxa on more arid sites (Ritchie 1982, Anderson and Brubaker 1994). In the coastal and mountain regions a

period of rapid glacial melt began, but forest migration into the region was delayed well beyond the time that climates became suitable for tree growth.

Across much of Alaska *Populus*, the first tree to appear, became abundant between 12,000 to 9000 14C yr BP. The species of *Populus* was probably *P. balsamifera* rather than *P. tremuloides* because leaves from *P. balsamifera* dated to 14,000 14C yr BP have been recovered from northern Alaska (Hopkins et al. 1981). It is likely that the *Populus* represents an expansion of gallery forests along rivers and around lakes. Tall statured *Salix* also appeared on the landscape in some areas during this time.

In the interior by about 9000 14C yr BP, *Picea* (*P. glauca*) appeared, probably by migrating from southern Canada after major shrinkage of the Laurentide ice sheet (Ritchie and MacDonald 1986). Between 7000-6000 14C yr BP, *P. mariana* and *Alnus* showed up on the interior Alaska landscape. *Alnus* probably existed in the interior earlier but pollen grains were sparse before this time. By 7000 14C yr BP, *Alnus* was found from the western Brooks Range in the north to the Canadian border in the east. By 6000 14C yr BP, all the modern constituents of the boreal forest were present in the region and by 4000 14C yr BP, vegetational distribution was very similar to modern (Anderson and Brubaker 1994).

In coastal Alaska, a different sequence and timing of events characterized the climate change following the end of the Pleistocene and the return of trees and the development of modern treelines (Anderson and Brubaker 1993, Anderson et al. 1994). The period from 8000 to 6000 years B.P. was characterized by dominance of shore pine (*Pinus contorta* var. *contorta*). From 6000 to 5000 years B.P. Sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*) succession was widespread in southeast Alaska. Further north in coastal southcentral Alaska, mountain hemlock (*Tsuga mertensiana*) attained its maximum predominance from 5000 to 2000 years B.P. (Heusser 1952). From 2000 to 200 years B.P. the climate became cooler and wetter, a hemlock maximum occurred, and pine expanded its range. The period from 1350 A.D. to about 1840 A.D. represents the Little Ice Age. Tree-ring reconstructions of some of the features of the climate of south coastal Alaska indicate the timing and the magnitude of climate change since 1600 A.D. (Wiles et al. 1996). Sitka spruce is still expanding its range westward in the Alaska coastal region (Veblen and Alaback 1996). Time and geographic barriers along the complex mountainous Alaska coast probably have prevented Sitka spruce from occupying all climatically suitable sites.

Climate control of treeline in Alaska and northwest Canada

Upper elevation and latitudinal treeline in Alaska and northwest Canada has been investigated from many different perspectives including community composition and structure (e.g. Larsen 1989, Viereck 1979, Viereck et al. 1992, Juday 1992) and dendroclimatology (e.g. Jacoby et al. 1996, Jacoby and D'Arrigo 1995). In general, height growth of trees at northern high latitude treeline is positively associated with summer temperatures (Junttila 1986, White 1974). Radial growth of white spruce at treeline in central Yukon Territory, Canada through the 1970s was significantly correlated (positively) with June and July mean monthly temperature, and even more strongly with total degree days above 10 C. However, a substantial moisture stress develops in some treeline trees late in the growing season in Alaska and Yukon, Canada. (Jacoby and Cook 1981).

A low elevation treeline associated with the transition between low elevation forest and grassland or steppe in Alaska and northwest Canada is less widely known. Because annual precipitation in central interior Alaska is low and summers are often warm, a precipitation deficit (excess of potential evapotranspiration over precipitation) develops. Calculated precipitation deficit values in Alaska include 9.5 cm at Bettles, 18.8 cm at Fairbanks, and 28.9 cm at Fort Yukon (Slaughter and Viereck 1986). Drought-limited plant species and vegetation formations at the lowest elevations of forest growth have been documented near the arctic circle in Alaska (Juday 1998, 1992). Recent research demonstrates that mean radial growth of stand-wide samples of white spruce on productive sites in Bonanza Creek Long-Term Ecological Research (LTER) site in central Alaska is negatively correlated with summer temperature and positively correlated with annual precipitation (Juday et al 1998).

Methods and study sites

Figure 1 shows the locations of 4 climate stations used in this study, and 4 treeline tree-ring study sites. Climate data were obtained from the Alaska Climate Data Center at the Geophysical Institute of the University of Alaska Fairbanks (early 20th century to 1940s), U.S. National Climatic Data Center (1940s to recent), and the National Weather Service Fairbanks Office (1997 and/or 1998). Treeline study sites include several of the main locations for treeline study or monitoring in Alaska.

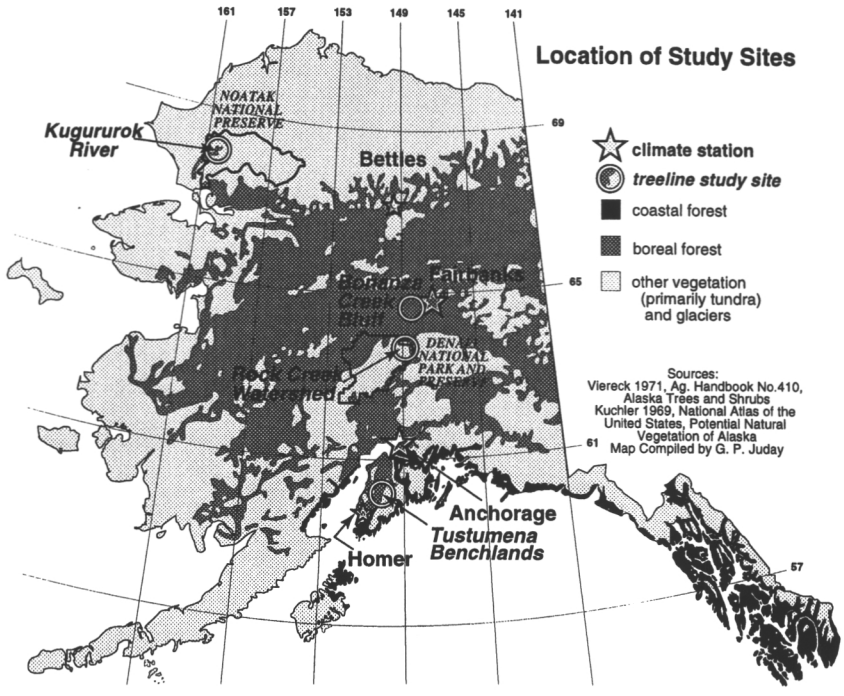


Figure 1. Location of study sites.

Climate stations and data

Bettles (66 degrees 55' N, 151 degrees 31' W; elevation 196 m) is located in a continental interior climate zone in the southern foothills of the central Brooks Range. The station is in lowland marginal forest along the Koyukuk River, 6.5 km east of the tundra-covered Alatna Hills. Station moves have been minor and urban effect from the small village is practically nonexistent. The climatic record extends from 1949 to 1997 when reporting from the site ceased.

Fairbanks (64 degrees 49' N 147 degrees 52' W; elevation 132 m) is located in the most productive part of the boreal forest at the confluence of the Chena and Tanana Rivers. The usable climatic record extends from 1906 to the present. The temperature record contains some effect of station move from a downtown location to the University Experiment Station and back (1911 and 1929), and a move to the modern airport location (1951 +). The urban heat of Fairbanks has increased winter minima at the station, especially in the second half of the record, but the data are still representative enough to be useful for correlation with tree growth.

Climate factors that are associated with treeline forests at high altitude and the North American Arctic treeline (D'Arrigo and Jacoby

1993, Jacoby and D'Arrigo 1989) are well appreciated. South slope grassland sites (bluffs) are recognized as the warmest and driest environments in interior Alaska (Viereck et al. 1986), but trees growing on these sites have not been specifically tested for climatic sensitivity previous to this study. Fairbanks temperature and precipitation data were combined into an index of climate favorability for white spruce radial growth on south slope grassland sites (bluffs). Upland white spruce radial growth in this region is positively correlated with precipitation and negatively correlated with warm season temperature (Juday et al. 1998). The climate index in this study is normalized growth year (September through August) precipitation minus normalized mean warm season (April through August) temperature for the same year as tree growth added to the same index calculated for the year prior to ring formation. Period of normalization was 1906-1998 for temperature and 1910-1998 for precipitation.

Anchorage (61 degrees 10' N, 150 degrees 01' W; elevation 35 m) is in a transition continental/maritime climate region typical of much of forested southcentral Alaska. The station is located at the head of Cook Inlet, on a triangle of rolling land bounded by partly mixed glacial meltwater and seawater. The record begins in 1916, but 12 missing monthly values have been reconstructed from nearby stations for the period 1916 through 1929. A few station moves (1923, 1926, 1938, 1943) preceded the current airport location (1953+).

Homer is at the border of the continental white spruce region and the maritime Sitka spruce region. The station is located near the tip of the Kenai peninsula, on the northwest side of Kachemak Bay (59 degrees 38' N, 151 degrees 30' W; elevation 20 m).The continuous record starts in November 1938 and extends to the present.

Treeline stands and data

The Kugururork River site (68 degrees 04' N, 161 degrees 50' W; elevation 210 m) is located in Noatak National Preserve (2,615,000 ha), a UNESCO Biosphere Reserve (Franklin 1979) which includes the northwesternmost limit of trees in North America. Studies of treeline white spruce growth and history have been conducted at Noatak recently (e.g. Rowland 1996). The site itself was described by Binkley et al. (1995).

Tree cores were collected in July 1997 in two adjacent stands separated by an old river side channel and differing <0.5 m in their terrace levels. For this study, we treat the two stands as one. We cored dominant trees spaced 10-30 m apart along five transects running parallel to the river, yielding 56 cores useable for age determination. All cored trees were tagged or mapped relative to a tagged tree for future re-

measurement. All cores were taken at 1.3 m above ground level. Number of years for growth from germination to 1.3 m was estimated based on a regression of rate of radial growth for the earliest 10 years in the life of the tree versus number of years to reach 1.3 m height (4 to 35) measured in seedlings and tree sections in interior Alaska.

All cores contained sections with densely packed, very narrow rings. All ring counts were verified by cross-dating. Especially helpful were weak ring boundaries (low development of latewood) in 1783/84, 1807/08, 1861/62, 1890/91, and 1896/97, and very narrow rings in 1978, 1975, 1950, 1940, 1922, 1912, 1910, and 1899.

Rock Creek Watershed Treeline site is a U.S. National Park Service Long-Term Environmental Monitoring (LTEM) site immediately upstream from the headquarters area within Denali National Park and Preserve (2,306,000 ha). Rock Creek Watershed includes 3 intensively monitored sites. The LTEM Treeline site in the watershed is located from 975 to 1,037 m elevation at the local elevational tree limit on a south-southeast facing slope of about 25 degrees. Vegetation is dominated by a dense dwarf birch (*Betula nana*) layer and varying amounts of white spruce, with thinleaf alder (*Alnus tenuifolia*) at the lower elevations and tundra species such as lichens and *Dryas octopetala* at the absolute elevational tree limit.

Tree cores were collected in September 1998 near the ground surface (21 to 80 cm above ground) from 26 white spruce located across an elevation gradient from about 925 m elevation to 1040 m. Tree height, growth form, and diameter were recorded. All trees sampled were at least 10 m outside the perimeter boundaries of the 3 permanent LTEM 50 m by 50 m monitoring replicate plots of the Treeline site. Cores were analyzed at the University of Alaska Fairbanks Tree-Ring Laboratory. Cross-dating was established from prominent marker rings. Minimum age from ring counts was adjusted by estimating number of rings to pith, if missed (mean 5.8 years, s.d. 6.5).

The Bonanza Creek Bluff site is in Bonanza Creek Experimental Forest (5,050 ha), a unit of the U.S. Long-Term Ecological Research (LTER) network (Van Cleve and Martin 1991). The Bluff site is a low elevation (130 m to 190 m) steppe-forest transition representing tree limit on a steep droughty south-facing slope. The steppe is a midgrass-shrub type in the Alaska Vegetation Classification System (Viereck et al. 1992), the warmest and driest environments in the LTER and interior Alaska (Viereck et al. 1986).

Cores were collected in July 1995 from 16 young trees (dates of earliest ring from 1948 to 1933) growing as isolated individuals along the perimeter of the grassy steppe or along a shallow ravine in the main

grassy opening. Trees were cored at the base of the ground. Penetrating cores were collected (from bark through pith to opposite bark) parallel to slope contour (n = 15) and if possible also perpendicular to slope (n = 1). Yearly ring-width series for each tree were calculated as the mean of all measurable radii (2 or 4) from the tree. Cores were measured at the University of Alaska Fairbanks Tree-Ring Laboratory. After visual inspection of individual ring-width plots, 14 tree ring-width series were de-trended with a negative exponential fit and 2 with a straight line fit; all ring-width series were normalized.

Tustumena Benchlands site is located in the Kenai National Wildlife Refuge (797,000 ha). Tree cores were collected on the Tustumena Benchlands, a gently sloping (2 degree slope) plateau abutting the western side of the Kenai Mountains between Skilak and Tustumena Lakes at 200-600m elevation. The vegetation is shrub tundra with crowberry (*Empetrum nigrum*) covered tussocks and occasional willow (*Salix* spp.) thickets. White spruce (*Picea glauca*) is slowly advancing upslope to colonize the plateau. Trees are open grown (no tree-to tree canopy competition) and are separated by tens to hundreds of meters.

Forty-nine trees were cored in 1997 at heights of 30-100 cm. Ring-widths were measured with a Velmex measuring bench to a precision of 0.01 mm at the Kenai National Wildlife Refuge laboratory, and all cores were cross-dated with the program COFECHA. Temperature correlations were made with monthly temperature data from 1932 to 1996 from Homer, AK, located 70 km SW.

Results

Size and age structure Figure 2 shows the structural characteristics of the Kugururork River stand. Tree heights range from 8 m to 20 m and diameters from 15 cm to 45 cm although few trees are > 30 cm diameter or > 16 m in height (figure 2A). Diameter and height of the oldest trees are smaller than youngest trees in the sample (figure 2A and 2B, r^2 of .10 and .07 respectively for the linear regression).

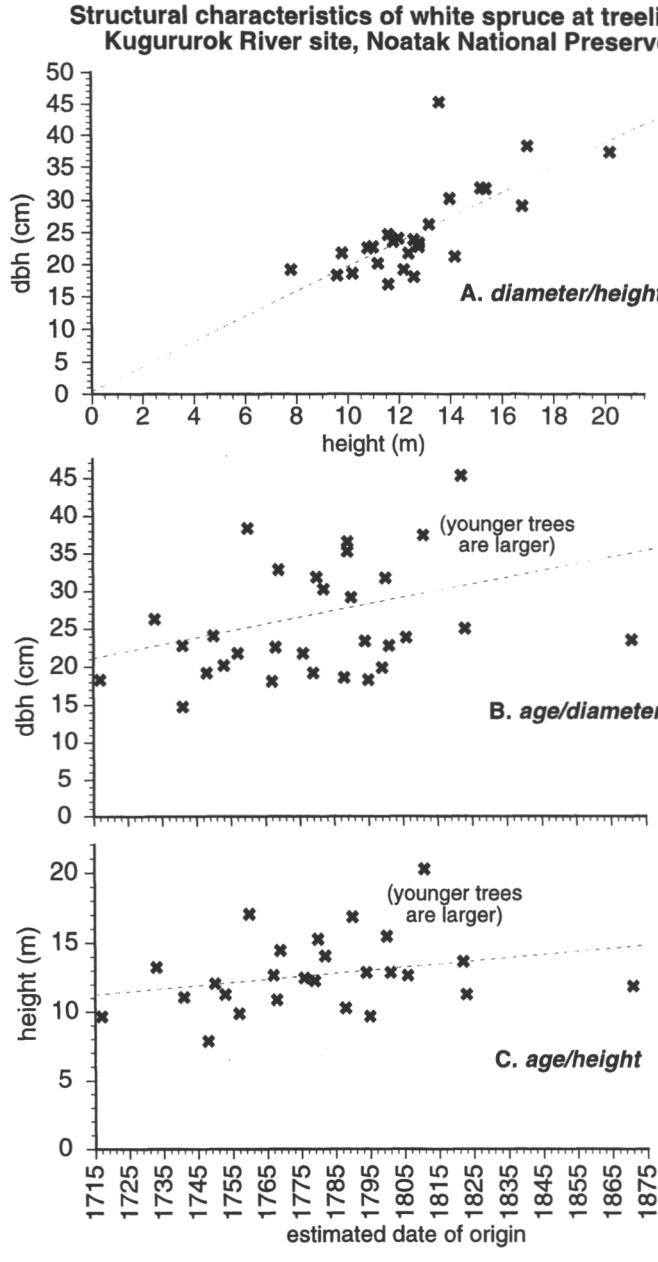


Figure 2. Structural characteristics of white spruce at treeline, Kugururork River site, Noatak National Preserve.

The Kugururork River stand is made up of trees with dates of origin centered on the decade of 1786 to 1795, and includes trees that originated from about 1720 onward; only 2 trees originated after 1825

(figure 3A). Because only large and/or dominant trees were sampled, age cohorts of trees originating in the 20th century were not sampled.

White spruce in the Denali LTEM Treeline stand are from about 5 m to 16 m in height and from about 10 cm to 35 cm in diameter (figure 3A). In the Denali LTEM Treeline stand diameter and height of the oldest trees are larger than youngest trees in the sample (figure 4A and 4B, linear regression r^2 of .56 and .49 respectively). The stand is made up of trees with dates of origin in 4 groups. About one third of the sample have dates of origin in the 3 decades from 1846 to 1875 (figure 3B-1). Slightly greater numbers of trees originated in the decades of 1906-1915 (figure 3B-2) and 1926-1935 (figure 3B-3) than the decades preceding and following. More trees originated in the decade of 1936-45 (figure 3B-4) than in any other.

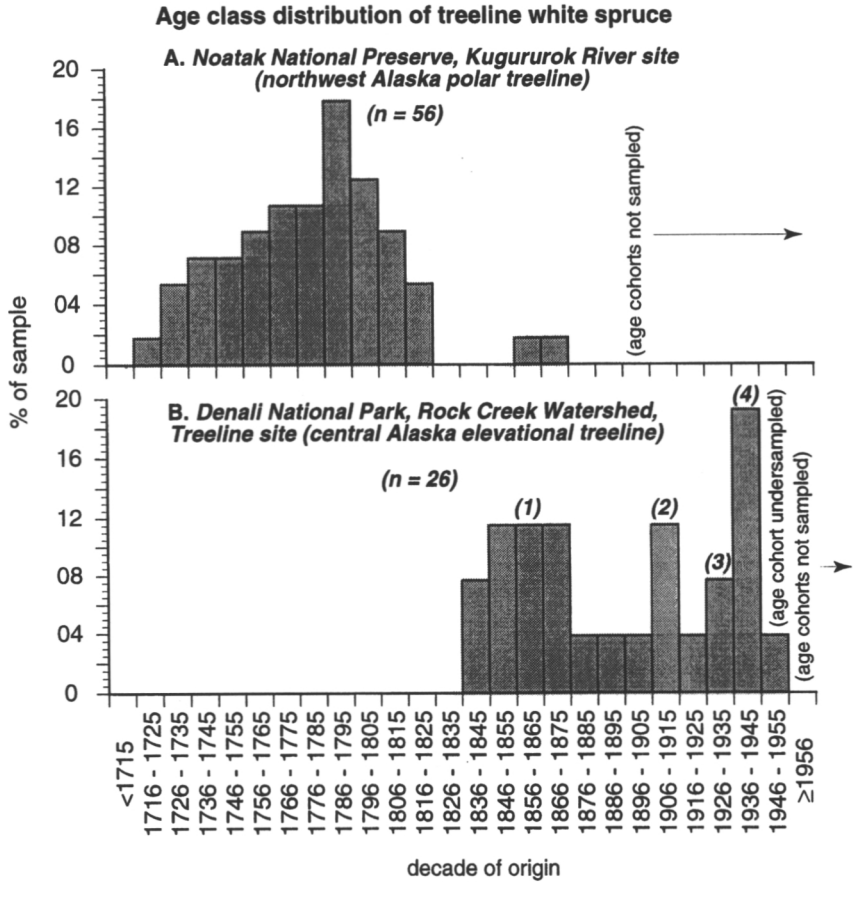


Figure 3. Age class distribution of treeline white spruce.

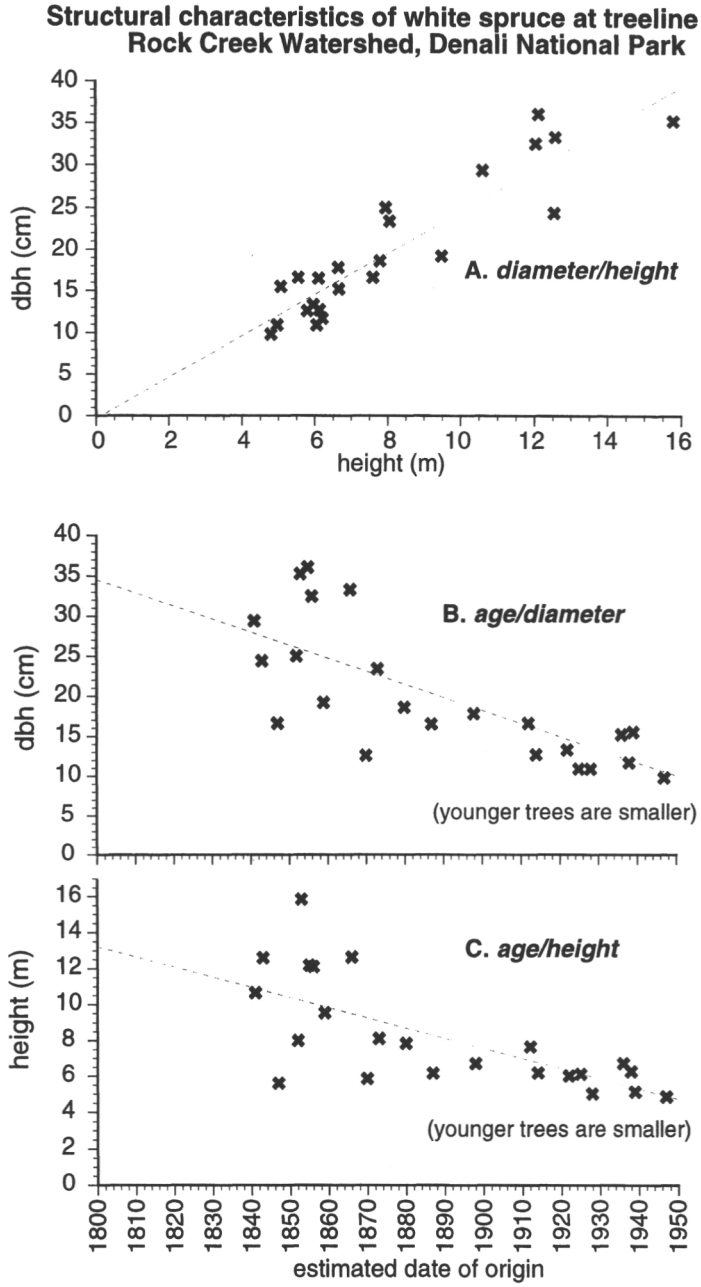
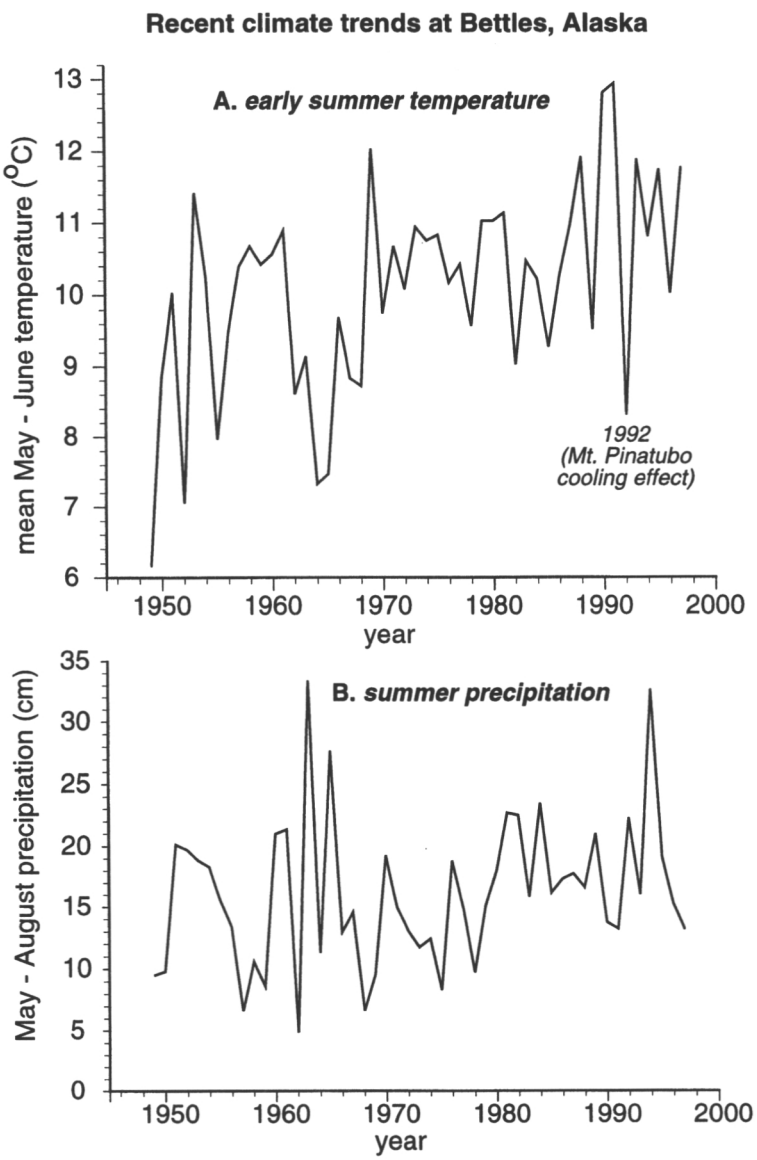


Figure 4. Structural characteristics of white spruce at treeline site, Rock Creek Watershed, Denali National Park.

Recent climate trends Early summer temperatures at Bettles in the central Brooks Range (figure 1) display a steady upward trend during the history of the station (figure 5A). The May - June mean temperature at

Bettles increased from the 6 to 10 °C range in mid-century to the 10 to 12 °C range in the 1990s. Two anomalies are a cool interval in the 1960s and the short, sharp cooling of 1992 associated with the hemispheric cooling effect of the eruption of Mount Pinatubo in the Philippines (figure 5A). Summer precipitation at Bettles has varied from nearly 5 cm to 33 cm (figure 5B). The trend of summer precipitation has been upward at Bettles, and the multi-year mean in the 1990s is at the highest level in



the record except for the mid 1960s.

Figure 5. Recent climate trends at Bettles, Alaska

Early warm season temperatures at Fairbanks have increased during the 20th century (figure 6). In the first half of the record mean April/May temperatures above 6 °C were relatively uncommon but were experienced frequently in the second half (figure 6). Years with particularly warm early seasons are 1912 and 1915 (figure 6-2), 1926 (figure 6-3), and 1940 (figure 6-4).

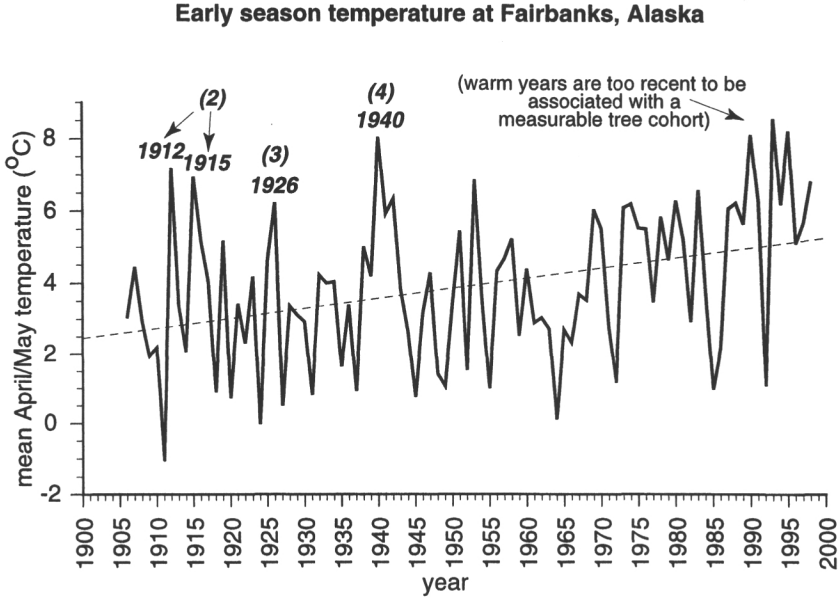


Figure 6. Early season temperature at Fairbanks, Alaska

The Anchorage and Homer climate stations display a rising trend of summer temperatures, with generally good agreement between the stations (figure 7). In the earliest years of the record Anchorage experienced mean summer temperatures in the 12 to 13 °C range, but especially since the mid 1970s summer temperatures have ranged from 13 to 15 °C (figure 7). Summer temperatures in maritime region of Homer are consistently about 2 °C cooler than at Anchorage, but in the 1990s summer temperatures at Homer have increased nearly to the level of summer temperatures in Anchorage at the beginning of the record in the 2nd and 3rd decades of the 20th century (figure 7).

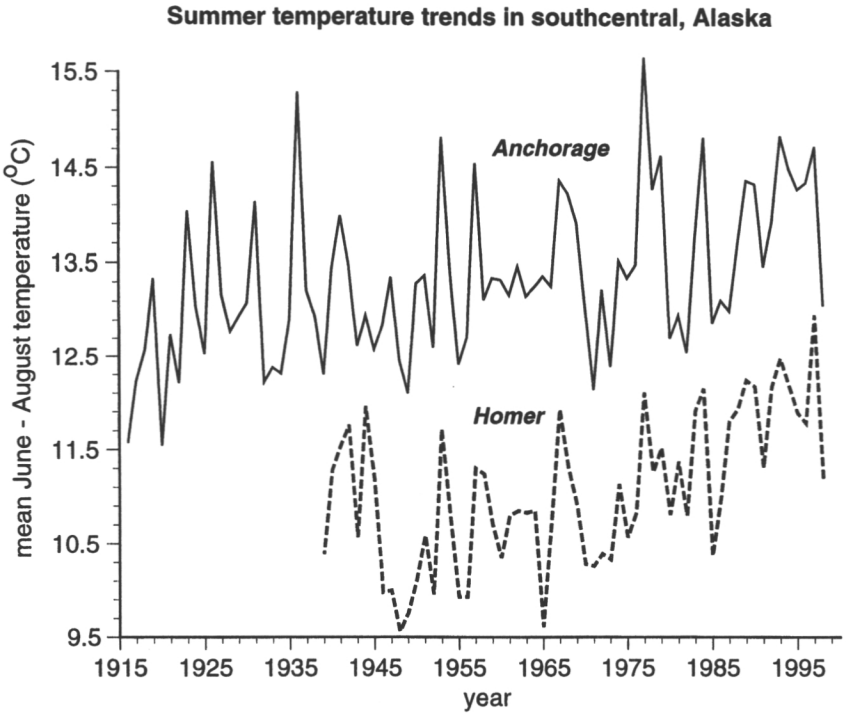


Figure 7. Summer temperature trends in southcentral, Alaska

Climate sensitivity of radial growth The young trees at Bonanza Creek Bluff first contribute measurable rings to the sample from the mid 1930s to the mid 1940s (figure 8A). In the mid 1980s a sustained period of low radial growth (figure 8A) appears in the Bonanza Creek Bluff trees at about the age they would be expected to be achieving their maximum radial growth. These trees were growing in open environments without canopy composition from neighboring trees, so canopy competition effects are minimal. The reduction in radial growth performance is particularly noticeable in de-trended, normalized radial growth for the Bonanza Creek Bluff sample, because in only one year after 1973 was ring-width index value greater than the sample average (figure 8B). The Fairbanks climate index (predictive index for white spruce growth) correlates at 0.729 (Pearson correlation coefficient) with the ring-width index (figure 8B).

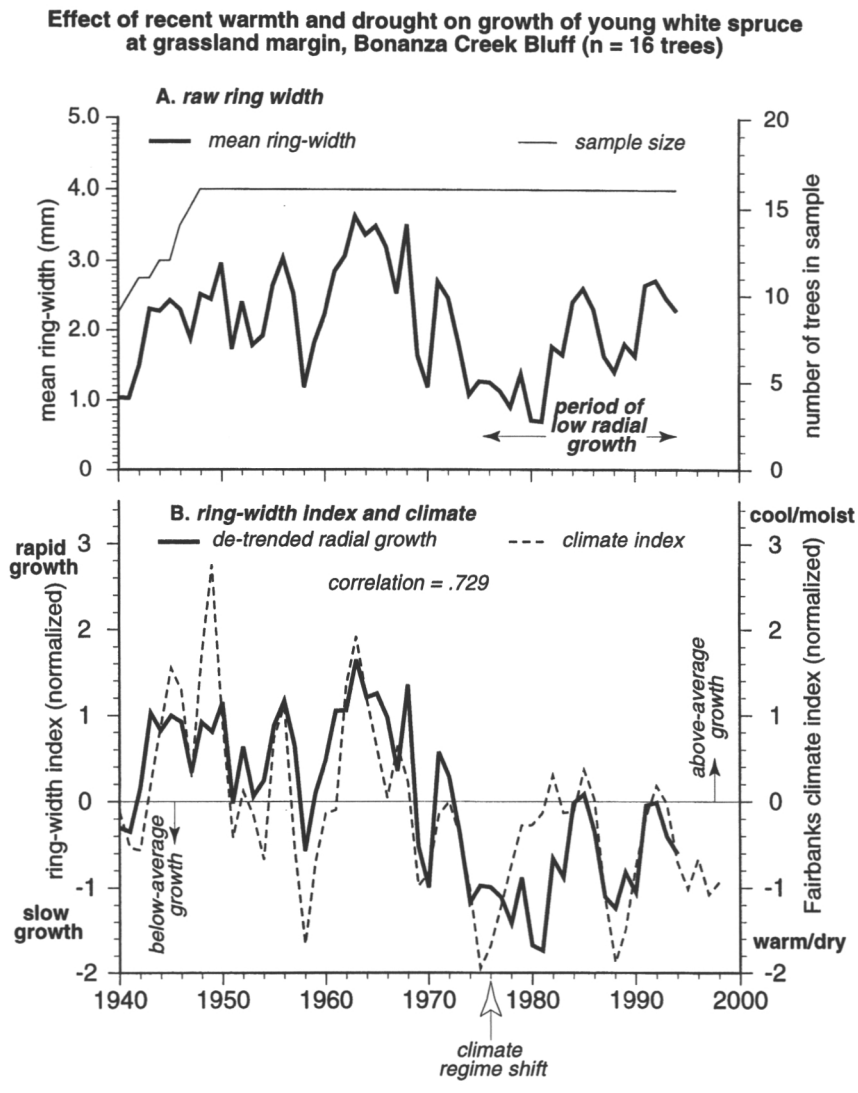


Figure 8. Effect of recent warmth and drought on growth of young white spruce at grassland margin, Bonanza Creek Bluff (n = 16 trees)

In terms of climate sensitivity, there are two populations of trees at the Tustumena Benchlands site on the Kenai Peninsula (figure 9). A minority of trees (20.3%) display a statistically significant ($p < 0.01$) positive correlation of ring-width with summer temperature in the year of ring formation and the previous summer. The majority of trees in the sample (79.7%) show no significant correlation between ring-width and any monthly temperature (figure 9).

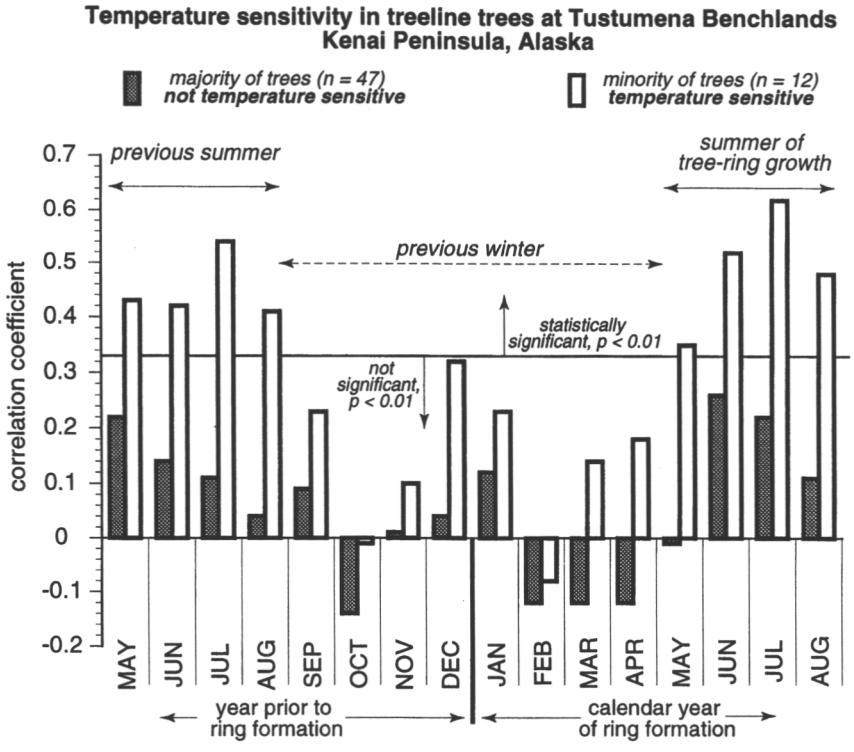


Figure 9. Temperature sensitivity in treeline trees at Tustumena Benchlands Kenai Peninsula, Alaska

Discussion

Latitudinal treeline - Kugururok River stand The structure of the Kugururok River treeline stands is unusual, because there is a weak tendency for the youngest trees in the sample to be largest in both diameter and height (figure 2B and 2C). Because diameter and height are fairly well related in the Kugururok stands (figure 2A), the largest trees in the sample in either diameter or height are most likely the trees that have grown the most overall in volume. This inverted size/age structure is consistent with a higher growth rate for trees established in the most recent years, and slower rates of growth for the oldest trees. The dates of establishment for the oldest trees are well within the range of the late portion of the Little Ice Age when temperatures were much less favorable than they have been during the 20th century. Trees established since the end of the Little Ice Age may have benefited from a less growth-limiting climate. In general, accelerated radial growth is found in treeline white spruce from western and central Alaska, associated with increased summer temperatures (Jacoby et al. 1999). However, certain treeline trees have begun to loose responsiveness to increasing temperatures because they have become increasingly moisture-limited

(Jacoby and D'Arrigo 1995). Locations that are experiencing increased summer precipitation along with increased summer temperatures such as Bettles (figure 5) appear to be particularly favorable for accelerated white spruce growth.

Seedling recruitment has not been a problem in most of the Alaska latitudinal treeline. Rowland (1996) reports that there are no gaps in the recruitment of white spruce seedlings in the Noatak National Park treeline in the last several centuries. Trees recruited in the 18th century predominate in the Kugururok River treeline stands (figure 3), consistent with those results. Across most of the Alaska northern tree limit, the Brooks Range form an elevational barrier. Even the strong recent warming in northern Alaska has brought only a relatively small additional elevational band within the temperature limits of tree growth. On the other hand, white spruce recruitment at the northwest Alaska treeline has occurred almost exclusively on primary successional surface, mostly floodplains and mountain earthslides or depositional fans (Rowland 1996), because thick organic mats of the tundra prevent spruce seedling establishment. If additional climate warming reduces the ability of the tundra mat to inhibit spruce seedling establishment and places Brooks Range passes and northern foothills tundra within spruce temperature limits, then a very rapid treeline advance could occur onto Alaska's north slope (Chapin and Starfield 1997).

High altitude treeline - Rock Creek and Tustumena Benchlands stands The age/size structure of the Rock Creek Treeline stand suggests that white spruce recruitment has occurred there since the end of the Little Ice Age. The sample is a mixed population of older, larger trees and young, smaller trees (figure 4). This continuous recruitment and the absence of trees with dates of origin before 1840 (figure 3B) is consistent with a recent and steady treeline advance in this part of the Alaska Range. It is particularly noteworthy that the periods of peak establishment of white spruce in the sample (points 2,3, and 4 in figure 3B) match both the timing and magnitude of warm early springs in central Alaska (points 2,3, and 4 in figure 6). Thus the years with particularly warm early growing seasons, a known triggering factor for white spruce cone crops (Zasada et al. 1978), match the decades of origin for the largest cohorts of Rock Creek Treeline white spruce.

These results are consistent with an advancing treeline in response to a warming climate. A first wave of spruce appears to have established in the decades immediately following the end of the Little Ice Age (1830-1870). These are now the largest trees in the upper Rock Creek watershed, located several hundred meters below the current treeline. A second wave of white spruce appears to have originated from cone crops triggered by the warm summers of 1912, 1915, 1926, and especially

1940. These are currently sapling and pole sized trees that define the local treeline. But favorable warm early growing seasons, especially since 1977, have occurred frequently in recent years and are correlated in time with the appearance of new smaller white spruce seedlings, and most recently with abundant cone crops measured directly in the Denali National Park LTEM program in 1997 and 1998.

At Tustumena Benchlands the fact that only a minority of trees within a random sample at treeline currently display a positive correlation between radial growth and summer temperature (figure 9) is quite unusual. The lack of temperature sensitivity at the currently established treeline suggests that summer warmth is not currently limiting, except perhaps on the most exposed sites. and that spruce could grow at still higher elevations. The increase in summer temperature in the late 20th century in southcentral Alaska is approaching 2 degrees C (figure 7). Physiological tree line thus appears to be advancing so rapidly that the trees have not kept up with it. Local residents in Kachemak Bay report that treeline has visibly risen at least several hundred feet since the 1940's (Yule Kilcher, personal communication). Sitka and white spruce on the flanks of the Kenai Mountains show a strong upslope gradient to younger trees. Furthermore, this process appears to be unidirectional, because old, dead trees are not present at treeline as would be true if treeline had temporarily receded at some point in the past. This unidirectional character of all climate-driven processes on the Kenai is quite striking, and suggests that this climate change is a long-term trend and not an oscillating process.

Additional evidence indicates that a strong climate warming has been underway in this part of Alaska since the mid 19th century. Wiles and Calkin (1994) developed a 2000y chronology of glacial advance and retreat on the Kenai Peninsula, and found that glacier front positions on the western side of the Kenai Mountains are controlled primarily by summer temperatures, whereas those glacial fronts on the Price William Sound side are controlled by winter snowfall. They showed that glacier fronts have generally been receding since the end of the Little Ice Age. For example, the terminal moraine of Grewingk glacier in Kachemak Bay was at its outermost position in 1858 and has retreated steadily more than 4 km since then.

Low altitude treeline - Bonanza Creek Bluff stand The Bonanza Creek Bluff stand is a particularly good indicator of the increasing, and now extreme, level of moisture stress in white spruce that occur in or near low elevation grasslands in interior Alaska. Most of the sample consists of trees that are growing in open grassland environments, with no canopy competition to affect the growth signal. The trees are all young (dates of origin just prior to the 1940s) so that age-related growth

effects are not a complicating factor. The degree of correlation with a simple index of summer temperature and annual precipitation is excellent, even including the fine points of year-to-year changes, and highly significant statistically. The period since the climate regime shift in Alaska in 1976, characterized by warming and summer drying, has been exceptionally stressful and radial growth of the trees is at a persistently low relative level (figure 8).

These results suggest that low elevation treeline white spruce in Alaska may be vulnerable to stress-related mortality from agents such as insects. The persistence or intensification of the recent climate warming in Alaska would make expansion of other vegetation at the expense of low elevation white spruce a distinct possibility. In central Canada, a considerable expansion of aspen parkland is projected under just such circumstances. In aspen parkland conifers are absent and aspen occurs as stunted patches within a grassland. Hogg and Hurdle (1995) applied climate changes projected from a doubling of CO_2 to 254 climate stations in the boreal forest region of western Canada. Previous studies have found that the southern boreal forest of North America is currently restricted to areas where annual precipitation is greater than potential evapotranspiration. They found that an increase in precipitation of 11% would not be sufficient to meet the increased water demand caused by a projected warming of 4° to 5°. Under such a climate, half of the western Canadian boreal forest would be transformed into aspen parkland. Aspen parkland occurs in the interior Alaska landscape today as a narrow zone separating steep south bluff grasslands and boreal forest.

Summary

(1) Treelines in Alaska show a strong response to the climate warming since the mid-19th century end of the Little Ice Age. The population structure of treeline white spruce in the central Alaska Range and southcentral coastal mountain regions is consistent with steady upslope recruitment of spruce in a warming climate since the mid 1800s. White spruce established since the Little Ice Age at the northwestern Alaska tree limit may be growing faster than spruce established earlier in colder conditions.

(2) White spruce at latitudinal and upper elevation treeline in Alaska are generally vigorous and have been able to reproduce steadily or at least at periodic intervals during since the beginning of the 20th century or earlier. Particular years with favorable weather for triggering white spruce cone crops include 1912, 1915, 1926, and especially 1940. Many of the well established treeline trees of today at central Alaska treelines may date from the 1940 or 1941 seed crop.

(3) A low elevation treeline in contact with grassland occurs in the dry central interior portion of Alaska. If recent warming and drying trends there persist or intensify, direct and indirect effects of moisture stress could result in white spruce retreat and expansion of grassland or aspen parkland.

(4) Strong climate warming has occurred widely across Alaska, especially since 1976. Some locations, such as the central Brooks Range have experienced increased summer temperatures and increased summer precipitation. An index of moisture stress composed of summer temperature and annual precipitation at Fairbanks records sustained, high levels of moisture stress since 1976.

(5) Only a small proportion of treeline spruce in the mountains of southcentral Alaska are sensitive to summer temperature. The actual elevational limit for growth of spruce in the mountains of southcentral Alaska may be substantially higher than the current elevation of established trees.

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