Tundra-Taiga Interface (TTI) - Rationale, History and Development Towards the Future

Introduction

Scientific Background

The position and dynamics of the Arctic-boreal boundary are major determinants for land atmosphere interactions at the circumpolar scale and for ecological and socioeconomic conditions at the local to regional scale. This zone, the "tundra-taiga interface" varies dramatically in width (up to hundreds of kilometers) throughout the circum-Arctic North and has thus a recognized exceptional importance, in terms of global vegetation, climate, biodiversity and human settlement. The size of the land area covered by the tundra-taiga ecotone is comparable with the area covered by Arctic sea ice or the circum-Arctic zone of isolated to continuous permafrost, to which the tundra-taiga interface has strong links. Position and response pattern to climate change varies strongly between oceanic and continental regions around the circum-Arctic. The particular vulnerability of the zone to changes in climate and land use is recognized, along with concern for subsequent alterations and shifts of its position with consequences for the entire Arctic region and the global climate through feedback mechanisms. Despite this recognition, comprehensive and large scale multidisciplinary scientific focus incorporating cause, effect, and importance of its past and present transformation to the biota and human societies, has been lacking and is the focus of TTI.

Feedbacks between these northern terrestrial systems and climate involves a broad range of scientific fields and the scope of TTI is covered by three main objectives

- To study past and present change in the tundra-taiga boundary including the mechanisms driving the changes and to predict future changes at a range of geographical scales;
- To assess the implications of current and predicted future changes for land use biodiversity and conservation ecosystem function and feedbacks to the climate system;
- To facilitate interactions and to stimulate collaboration between different disciplines studying tree line processes.

The cross-discipline focus is interactions between the terrestrial vegetation and climate and in particular the significance of main structuring components of the vegetation such as occurrence of forests, woodlands and trees at local, regional and circumpolar scales. High latitude forests and tundra areas provide essential feedbacks to the global climate through for example their capacity to store large amounts of carbon and their ability to transform solar radiation to sensible heat. A change in growth rate and area covered by trees would change the CO_2 uptake capacity of the regions, and replacement of tundra by forest (especially evergreen) would decrease regional albedo and thus enhance warming. Further, changes in tree cover interact with the occurrence and distribution of continuous and discontinuous permafrost. Consequently, a change in range position would involve series of large ecosystem consequences with repercussion on occurrence and vitality of forests and trees in the transition zone towards the Arctic and thus further affecting the Arctic climate and the inhabitants of the Arctic.

Understanding the behavior of climate systems requires profound knowledge of its components – atmosphere, hydrosphere, lithosphere, and biosphere – and how these interact with each other, but holistic approaches are sparse and difficult to achieve. Largely, the diversity of processes and changes within the terrestrial component has been excluded or avoided in attempts to model future development of climate systems. The system is non-linear and natural variability of feedback processes and responses to external forcing make the system highly complex. Use of numerical models, present-day climate data and reconstructed paleo-climate data offers analyses of a large range of possible states, which is needed as future climate is foreseen to differ significantly from last centuries. However, the structure of present ecosystems making up the biomes of today are not identical to the ones that formed the paleo archives, and can thus not be assumed to respond in the same way to abiotic and biotic forces. Consequently, profound knowledge and data on recent and ongoing responses to climate is needed and have to be included in models of future responses and development of the Arctic climate.

A continuously shifting balance between dominating air masses has changed and is changing the structure of for example the boreal forest, the forest-tundra ecotone and the tundra. These structural changes include shifts in range limits of species and systems. During the last 10,000 years or so the main range limit shifts have been retraction and a large part of the area north of the present Arctic treeline thus in a Holocene perspective belongs to the zone with discontinuous to continuous boreal forest and woodlands. Thus, the zone between the closed boreal forest and the treeless tundra including latitudinal treelines has a long history of response and adaptation to changes in climate conditions. It is generally assumed that this climate-sensitive ecotone including the northern limit of the boreal forest is determined by the summer position of the Arctic front. However, the boreal forest itself may significantly influence the position of the front, mediated through forest structure and surface roughness at local, landscape and regional levels.

Models of future vegetation distribution suggest a rapid and dramatic invasion of the tundra by taiga. Such changes would generate both positive and negative feedbacks to the climate systems. However, the balance between negative and positive feedbacks is largely unknown as important variables such as snow (timing, duration, quality), changed forest cover, peatland performance, and fresh water flows into the Arctic Ocean are to a varying degree or not at all included in the models. Additionally, feedbacks amplifying climate warming have been of main concern during the last decades, thus restricting interpretation of a broader range of potential responses. Further, there are many uncertain links in the system; for example there is no straightforward relationship between increased temperature and reduced snow cover, or between reduced snow cover and increased growing season length. The main reason is prevailing regional differences along latitudinal gradients, coast-inland gradients, and along altitudinal gradients conditioned by the mean position of 0°C in space and time.

Most models of future responses, generally based on present day biome distributions and future biome distributions as predicted by $2xCO_2$ levels, forecast a latitudinal shift in the location of the forest-tundra ecotone by several hundred kilometers. Such changes would have significant consequences for ecosystem diversity and functioning, regional socio-economy, as well as consequences for the climate system at the regional to global scale. Changes of the forest-tundra zone strongly influence energy exchange between the biosphere and the atmosphere. The involved feedbacks between the physical climate and vegetation are essential for the entire circumpolar north. These feedbacks occur through energy exchanges at the surface, but extend through the lower atmosphere and, ultimately, the entire atmosphere. The primary control on the energy balance is the surface albedo (the proportion of the incoming solar radiation that is reflected) – which determines the overall absorption of solar radiation at the surface. The contrast in surface characteristics between the tundra and the boreal forest is considerable particularly in the winter when the tundra is snow covered. This variation causes massive changes in energy fluxes at the surface and hence temperature on the ground and in the atmosphere, with consequence for vegetation development, carbon fluxes, permafrost and hydrology. The heat flux into the ground is determined by the surface roughness, the physiological properties of the vegetation, and the thermal properties of the vegetation and upper soil layers. All these surface properties are substantially altered by the presence of a snow cover. However, the nature of the vegetation will itself influence the distribution of snow and thus the impact of snow cover – leading to a number of additional interactions.

Considering that terrestrial areas cover vast parts of the circumpolar north and that the forest-tundra boundary stretches approx. 14 000 km around the Hemisphere, any change of its position or structure will cause massive changes of the feedback system between the climate, other components of the abiotic environment and the biotic environment. Additionally, the climatic significance of the terrestrial component in regional to global climate systems has changed through history due to variation in areas covered by forest, tundra, wet lands

A range of expected vegetation responses to climate warming includes for example increased growth and productivity through increased photosynthesis and nutrient availability, increased seed reproduction vs. vegetative reproduction, range adjustments, and new structure and composition of vegetation communities. However, it can be questioned, to what degree this has been recorded and if there is other major impact factors or processes that complicate the scene? The answer to the first question is not straightforward due to the fact that there is a lot of published information confirming both expected vegetation responses and indifferent or opposite responses. The answer to the second question is of course Yes, and the main factors are human land use, grazing pressure, vegetation inertia, recovery from previous disturbances, and shift in disturbance regime. Depending on the nature (kind, frequency and magnitude) of these factors or disturbances to the system, it may take several centuries to recover to the pre-disturbance state. However, during the meantime, climatic prerequisites for the previous vegetation state will have changed and the previous state will thus not be reached. Consequently, it can not be known where studied systems are situated along the disturbance-recovery time gradient, and systems situated at, for example, relict positions (i.e. stronger correspondence to previous environmental conditions than present) will respond completely different to imposed disturbances compared to systems in balance with recent environmental conditions. Further, recent estimates of annual change in plant growth (net primary production) using satellite images and climate data for 1982 to 1999 show large differences at the regional scale around the circumpolar north. Increased growth is shown for central Alaska, eastern Canada, Fennoscandia, and European Russia, and decreased growth for northern Siberia to eastern Alaska, northwestern Canada, and the Kola Peninsula. Considering this distribution of regions with net increase and decrease, respectively, there is an apparent risk of overestimating responses at the circumpolar level as available measured ground data for inclusion in models of future responses mainly represents areas with increased growth.

The forest-tundra boundary includes a set of distribution limits, (timberline, forest-line, treeline, species line, historical treeline) which are of significant importance in studies of spatiotemporal responses to environmental changes. Towards Arctic areas, the boundary may cover hundreds of km and towards alpine areas some hundred altitudinal meters. Along mountain chains intersecting into the Arctic, a complex system of both alpine and Arctic responses has to be considered. The scientific field of treeline dynamics considers the entire transition zone from the closed forest to the treeless tundra. Different environmental factors and disturbance agents are acting at the different limits and their individual importance change through time. For example, fire may be a strong determinant in the forested part of the transition zone but of no significance at the species line in some regions but be temporarily significant throughout in other regions; and wind might be highly significant through time at the species line and treeline but only rarely or occasionally at the timberline.

Since the mid-Holocene, the forest-tundra boundary vegetation in the northern hemisphere displays generally decreasing stand density, retreating forest- and treelines, and changes in species composition as a consequence of deteriorating climate conditions. The climatic improvements since the Little Ice Age (i.e. end of the 19th century) has caused stand densities to increase and different distribution limits to advance. However, there are large regional differences including evidence of fragmentation and withdrawal, and large differences between specific time periods. For example, the climatic improvement (warming) during the 1930's resulted in generally increased tree growth but the warming during the 1990's did not show the same response. Structural changes result from a series of mechanisms, governed directly or indirectly by climate variability and small- to large-scale disturbances. Disturbance is a central factor in vegetation dynamics and in translating climatic change into vegetation response. Consequently, knowledge of the disturbance regime is essential for understanding and modeling system responses. Factors such as temperature and precipitation regime (trends and variability), precipitation quality, occurrence of warm spells in winter and cold spells in early growing season, moisture conditions (drought vs. saturation), wind activity, changes in frequency, intensity and distribution of fire, fungi, and herbivores (insects, ungulates, lemmings), and human impact are important to consider in order to reach reliable predictions.

Insect outbreaks have recently got renewed regional attention. In Alaska, for example spruce bark beetle outbreaks over the last 15 years have killed trees over an area twice the size of Yellowstone National Park possibly as a consequence of a long run of warm summers. In northern Fennoscandia, the area affected by autumnal moth outbreaks has increased. These insects that during severe outbreak years may kill birch forests over large areas have a cyclic occurrence with some 12-15 years between regional peak years. The outbreak frequency is predicted to increase in a warmer climate and could thus cause radical structural changes at local, landscape and regional level. Forest recovery to the pre-outbreak state at these different spatial scales depends largely on intensity and spatial extent of the outbreak, post-outbreak climate conditions and species interactions. Host species will suffer at the expense of non-host species leading to changed distribution and balance between for example evergreen and deciduous tree species. In addition to tree layer changes, the outbreaks generally cause field layer changes commencing a new grazing regime dominated by other herbivores operating with deviating intensity and frequency compared to the pre-outbreak system. These interactions may together with changes in dominating climate regime cause a shift in state of the system characterized by new dominating tree species or formation of sub-Arctic tundra areas with long-term resistance to tree invasion. These alternative paths of development will produce completely different feedback to the climate system both when compared to each other and to the pre-disturbance vegetation.

and water. In the predicted future, its importance is likely to increase along with, for example, the decrease in Arctic sea ice distribution because of spatial changes in mean seasonal and annual albedo around the circumpolar north. Consequently, this urgent need to include a broader range of terrestrial components, including internal and external feedback mechanisms, into models aiming at realistic regional and circumpolar climate scenarios is the TTI rationale.

Project history

The IASC project *Tundra-Taiga Interface* (TTI) was initiated in 2000 at an international workshop held at Abisko Scientific Research Station with the main aims to *i)* review and collate relevant existing research effort, expertise and programs; *ii)* bring researchers together in international workshops and conferences; *iii)* assess the state of knowledge at these meetings; *iv)* establish communication and networking between interest groups; *v)* identify and prioritize relevant research and research consortia; *vi)* implement top priority projects; and *vii)* publish reviews of the current knowledge. The results of the initial workshop, held in Abisko, were published in an Ambio volume in 2002: "*Dynamics of the Tundra-Taiga Interface*" (Report 12).

In 2004, the direction of the project shifted from collating and synthesizing new knowledge to identifying and initiating priority research activities, with the science plan and implementation plan as central tools. At the start-up of activities directed towards the IPY 2007-2008 the circumpolar and interdisciplinary approach of TTI and its focus on the southern delimitation zone of the Arctic formed the platform for the IPY 2007-2008 core project *PPS Arctic* (www.ipy.org #151) endorsed by IPY 2007-2008 Joint Committee in November 2005. Further, since 2005 TTI is merged with ICARP II WG 8.

Results and Achievements

PPS Arctic - a multidisciplinary and circumpolar research cluster

Project description

The *PPS Arctic* – *P*resent day processes, *P*ast changes, and *S*patiotemporal variability of biotic, abiotic and socio-environmental conditions and resource components along and across the *Arctic* delimitation zone – is a multidisciplinary research cluster composed of individual projects suggested to IPY 2007-2008 Joint Committee and existing national and international projects jointly seeking to explore current processes, past changes and spatiotemporal variability of biotic, abiotic, and socio-environmental conditions and resource components along and across the transition zone between Arctic and boreal regions.

The *PPS Arctic* is composed of four scientific modules:

I. Global change effects on the Arctic-boreal transition zone and modeling structural changes;

Brooks Range, Alaska.

II. Past history and broad-scale temporal variations of the transition zone;

III. Classifying vegetation, land cover and land use, and their spatial variations, by remote sensing and landscape analysis;

IV. Land use and development of the Arctic-boreal transition zone through the joint perspective of local traditional and scientific knowledge.

The unifying foci among the modules are defined by:

SPACE – The transitional zone between the boreal forest and the open treeless tundra;

TIME – The Holocene, the present and the next 100 years;

SCOPE – Interdisciplinary research, monitoring change, and sustainable resource use.

The main aim is to obtain an understanding of:

1. The controls on the location and pattern of the zone;
2. The effect of global change on the location of the zone;
3. The feedback effect of the character and location of the zone on the global climate.

Implicit in these three items is consideration of the role of human societies inside and near the transition zone. This refers both to the responses of human communities to changes in the zone and to their impact on the ecotone. The *PPS Arctic* cluster provides a framework for a coordinated and integrated scientific effort to understand the dynamics of the Arctic-boreal transition zone, and ensures that results can be used in multiple contexts including informed decision making by the public and by policy makers.

Specific objectives in focus in the core project are:

- To develop effective techniques and carry out quantitative spatial and temporal analysis of the location of transitional ecosystems within the circumpolar Arctic-boreal transition zone;
- To understand ecosystem and geosystem controls and responses in different compartments of the zone, both resilient and sensitive;
- To build realistic models of transition zone dynamics;
- To validate the models by ground level observations, dependent on scale and land use history;
- To use them to implement a program of ecosystem, geosystem, and landscape analysis, examining the effects of global and local change on species, communities, and ecosystems;
- To assess the socio-economic impacts of potential future changes in the transitional zones, incorporating results into an expert information system, which will be utilized for estimating climate change responses, sustainable ecosystem management and landscape planning in support of policy decisions;
- To exchange methods on climate change monitoring, sustainable land use strategy and science/policy issues, and use them as a tool in forecasting ecosystem changes and options for mitigation.

Unifying themes. To realize the main aim and specific objectives PPS Arctic focuses on a set of unifying themes: Terminology, location, history of shifts, interface processes, model realism, effects of shifts, detecting shifts, and human societies and shifts.

Tasks. A range of tasks will be pursued, linked to these themes:

- Standardize terminology;
- Determine current location and characteristics using remote sensing data, aerial photographs, geographical information systems and field campaigns, as well as using local and indigenous knowledge;
- Study the history of tree distribution patterns more comprehensively using multiple techniques such as tree-ring analysis, macrofossil, stomata and pollen analyses coupled with molecular genetics;
- Study environmental conditions across the zone by using, for example, meteorological, geomorphological, hydrological, and permafrost measurements;
- Study population dynamics, population ecology, developmental phenology, and physiological ecology of present tundra-taiga species;
- Study the effect of tree cover on ecosystem ecology including greenhouse gas fluxes and energy balance across the boreal-Arctic interface (feedback effects);
- Study the nature and effect of present and past disturbances such as fires, insect outbreaks and human activities on the nature and location of the zone and its sustainable use;
- Study socio-economic and ecosystem management conditions across the zone, which includes assessment of human impacts on the nature and location of the zone and consequences for human activities and strategies for sustainable development;
- Build process-based models and predictions for the effects of environmental change, with a greater degree of realism than current models;
- Conduct scientific manipulation experiments and analyze data from large-scale human activities such as engineering and forestry projects to test the models.

Project structure and products

The *PPS Arctic* brings together complementary research groups of different disciplines (terrestrial ecology, biogeography, physical and human geography, paleoecology, remote sensing, GIS, traditional knowledge, socio-economics, sociology) and nationalities with expertise from a range of sites in the Arctic and its neighboring regions, as well as from sub-Antarctic and alpine regions where sites for studies of homologies are included in some of the projects within the cluster. The project has a strong focus on integration across disciplines. Successful tools are common protocols and sites, student and principal investigator (PI) exchange between projects and disciplines, coordinated field activities, and multi- and inter-disciplinary workshops.

Major scientific products

- new integrated knowledge and models identifying and quantifying the multitude of biotic and abiotic forces governing transformation of the transition zone through space and time; how these are likely to affect the sustained production of renewable resources on which local cultures depend; and how human societies affect the location, structure and resilience of the zone;
- high quality information packages (publications, website, workshops) for the public;
- a database with uniform field data that will outlive IPY 2007-2008 and be of long term use for the scientific community;
- topic-specific and multi-disciplinary scientific publications published in journals of highest possible reputation, in books, and the IPY 2007-2008 book series (e.g. Pole to Pole; #79);
- recruitment of new young skilled scientists through customized MSc and PhD programs;
- important new knowledge input to the international science community for elaboration into future development within networks/programs such as: IASC, ICARP II, ACIA, AMAP, CAFF, Intergovernmental Panel on Climate Change (IPCC), IPA.

Main geographical areas

The project with its circumpolar approach focuses on a set of regions across northern North America and Euro-Asia: Alaska (Seward Peninsula, Brooks Range), Western Canada (southern Yukon, south-western NWT), Central Canada (west of Hudson Bay), eastern Canada (Quebec, Newfoundland), Northern Scandinavia, western Russia (Kola Peninsula, Komi).

Implementation History and Timeframe for project activities

The activities within *PPS Arctic* are characterized by a period of intensified activity during 2007-2009, but the organization with strong international cooperation and integration, within and between scientific fields, will warrant for a development of a long-term scientific network with focus on processes in the tundra-taiga zone that will outlive IPY 2007-2008. This process was started at the first annual core project meeting in Quebec City in February 2006.

2004-2005 Proposal development by the TTI project group.

2005 Project endorsement by IPY 2007-2008 Joint Committee, 3 November.

Project group meetings during ICARP II, 10-12 November.

2006 First annual international core project meeting in Quebec City, 16-18 February 2006 where *i)* all included projects were presented and discussed in terms of their role and contribution to the interdisciplinary and circumpolar approach of *PPS Arctic*; *ii)* development of a long-term scientific network with community involvement were discussed; and *iii)* the development of common protocol was initiated

2006 Funding proposals by individual projects to national and international funding agencies

2007 Second annual meeting, Tromsø 20-23 March. Common protocol workshop and fieldwork planning

2007-2009 Field work, data analyses, publication of individual results. Information packages and workshops

2008-2010 Joint coordinated publications at module and main cluster level

2010-- Continued network activities (results and products will be presented at annual meetings)

Annual meetings are held alternately between North America and Europe, with the following agreed suggestions: St Johns, Newfoundland 2008; Sweden or Russia 2009; and Edmonton or Whitehorse 2010.

Legacy

The project will leave an infrastructure of sample plots with accessibility to future research projects and improved links between research groups and field stations. Further, the envisaged construction of a monitoring system consisting of a land-use impact model based on Geographic Information System (GIS) and remote sensing data will have highly beneficial potential as a planning tool for future impact assessments by related governmental and non-governmental organizations.

PPS Arctic involves partners/scientists from traditional polar nations and others with experience from Polar Regions and transitional zones. In particular, young scientists and scientists from both polar and non-polar nations are encouraged to join the project group. The project will, thus, produce a new generation of both topic specific and inter-disciplinary trained and skilled scientists, prepared to bring new knowledge on to the next generation of scientists and the future society.

In addition to a legacy of scientific communication and non-technical publications generated from the *PPS Arctic* "snapshot" research activities during 2007-2008, a highly important legacy will be the long-term network that has been initiated and that will further develop during and after the IPY 2007-2008 period.

Achieved funding

IASC (2000-2007)

Royal Swedish Academy of Sciences (2000)

Climate Impacts Research Centre (2000-2002)

Norwegian Institute for Nature Research (2002-2006)

TTI/PPS Arctic study site, Khibiny Mountains, Kola Peninsula, Russia.

The UK National Environment Research Council Airborne Research and Survey Facility (NERC ARSF) (2003-2004)

Research Council of Norway, IPY 2007-2008 funds (2006-2010)

Canadian IPY 2007-2008 funds (2007-2010)

Additional travel grants/support given by universities/institutes/councils to individual network members are not listed.

Field activities:

Ongoing field activities in Alaska, Canada, Nepal, Norway, Russia, Sweden,

List of Publications

Annual Reports to IASC: 2000-2006

Callaghan, T.V., Crawford, R.M.M., Eronen, M., Hofgaard, A., Payette, S., Rees, W.G., Skre, O., Sveinbjörnsson, B., Vlassova, T.K. and Werkman, B.R. 2002. The dynamics of the tundra taiga boundary: an overview and a coordinated and integrated approach to research. *Ambio, Special report*, 12: 3-5.

Publications by Individual Members: not listed

Contact Information

Project coordination

The project is coordinated from Norway by **Annika Hofgaard**, Norwegian Institute for Nature Research, in close cooperation with the co-coordinator **Gareth Rees**, Scott Polar Research Institute, University of Cambridge, UK, and the Project Steering Board.

Project Leader

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Young scientists currently involved in TTI/PPS Arctic

Postdocs:
Ryan Danby and **Brian Starzomski**, Canada; **Anna Govorova** and **Alexandr Kanatjev**, Russia; **Mikhail Zimin**, Norway.

PhD students:
Ingrid E. Mathisen, Norway; **Krishna Babu Shrestha**, Nepal/Norway; **Elena Khorokhorina, Valentina Kostina, Andrey Medvedev** and **Ekaterina Shipigina**, Russia; **Rik Van Bogaert**, Belgium; 5-7 PhD students to be appointed within PPS Arctic Canada.

MSc students:
Sigrun Aune and **Staffan Dovärn**, Norway; **Miguel Cardoso**, Portugal; **Peter Glasov, Anna Mikheeva, Marina Ivanova, Svetlana Nikolaeva, Valentin Rasputin** and **Sergey Zharenov**, Russia; 10-12 MSc students to be appointed within PPS Arctic Canada.

Website

A *PPS Arctic* website is under construction.