The Dynamics of the Tundra-Taiga Boundary: An Overview and Suggested Coordinated and Integrated Approach to Research

Terry V. Callaghan, Robert M.M. Crawford, Matti Eronen, Annika Hofgaard, Serge Payette, W. Gareth Rees, Oddvar Skre, Bjartmar Sveinbjörnsson, Tatiana K. Vlassova and Ben R. Werkman

The tundra-taiga boundary stretches for more than 13 400 km around the Northern Hemisphere and is probably the Earth's greatest vegetation transition. The trees that define the boundary have been sensitive to climate changes in the past and models of future vegetation distribution suggest a rapid and dramatic invasion of the tundra by the taiga. Such changes would generate both positive and negative feedbacks to the climate system and the balance could result in a net warming effect. However, the boundary is becoming increasingly affected by human activities that remove trees and degrade forest-tundra into tundra-like areas. Because of the vastness and remoteness of the tundra-taiga boundary, and of methodological problems such as problematic definitions and lack of standardized methods to record the location and characteristics of the ecotone, a project group has been established under the auspices of the International Arctic Science Committee (IASC). This paper summarizes the initial output of the group and focuses on our uncertainties in understanding the current processes at the tundra-taiga boundary and the conflicts between model predictions of changes in the location of the boundary and contrasting recently observed changes due to human activities. Finally, we present recommendations for a coordinated international approach to the problem and invite the international community to join us in reducing the uncertainties about the dynamics of the ecotone and their consequences.

BACKGROUND

The papers presented in this special issue of Ambio result from a conference and subsequent discussions of a Steering Committee that were initiated as an approved project within the International Arctic Science Committee's (IASC) activities. The project was established because it was recognized that the latitudinal treeline or tundra-taiga boundary is an exceptionally important transition zone in terms of global vegetation, climate, biodiversity, and human settlement. It stretches for more than 13 400 km around the Northern Hemisphere through areas that are experiencing different types of environmental change for example, cooling, warming, or only small temperature change, changes in the amount and quality of precipitation, and changes in land use coupled with possible depopulation.

We know that the latitudinal treeline has responded to changes in climate in the past 10 000 years and more (1) and we expect it to change as our current climate changes due to global warming (2). However, climate is only one of a suite of environmental factors that are now changing and a critically important challenge is to determine how human impacts in the ecotone will modify the zone's expected response to climate (3). The outcome of the various impacts on the location and characteristics of the tundra-taiga zone will have important consequences for the ways in which the new areas of tundra and taiga affect regional—and perhaps global—climate through impacts on carbon storage, albedo and hydrology (4). It will also affect human activities (3).

The *Dynamics of the Tundra-Taiga Boundary* initiative is operated by a Steering Committee of representatives of nations with Arctic territories or interests, and officers who are not necessarily national representatives. The Steering Committee was nominated at the first international workshop held in April 2000 at Abisko, northern Sweden, and approved by IASC.

The current objectives are:
- to assess the vulnerability of the tundra - taiga interface and its associated human societies to environmental change;
- to identify and quantify interactions, including feedbacks, between the biosphere and atmosphere related to the dynamics of this interface;
- to model and predict future changes in the location and characteristics of the interface;

To achieve these objectives, the Steering Committee is initiating and pursuing the following activities:
- stimulating international and interdisciplinary collaboration;
- providing expert advice to regional, national and international processes;
- standardizing terminology;
- determining the current state of the tundra – taiga interface, e.g. its location and characteristics;
- continuing to develop the scope and representation of our initiative;
- disseminating relevant information at various levels of scientific understanding.

The foci of interest of the project are:
- *In space,* the tundra - taiga ecotone between the closed boreal forest to the South, and the open treeless tundra to the North.
- *In time,* the Holocene, the recent past (200 years), the present, and the next 100 years.
- *In scope,* cross-cutting issues such as environmental degradation and change, monitoring and detection of change and sustainable resource use.

This first volume resulting from the project seeks to assess the state-of-the art related to the 3 objectives above. The brief overview presented in this paper comments in the broadest terms on the major issues that will be raised by the detailed chapters and then proceeds to make recommendations on how the Steering Committee's proposed activities can be accomplished within the international research community.

MAJOR CERTAINTIES AND UNCERTAINTIES

General Characteristics of the Tundra-Taiga Boundary

Despite research spanning nearly one century on the treeline and related phenomena, the lack of standardization of terminology and the wide variation in methodology applied to locate, characterize and observe changes in the boundary have resulted in a rather poor understanding of the current location and characteristics of the boundary. A compilation of our present knowledge of the latitudinal treeline location even at a global scale shows particular areas of uncertainty such as the Lena Delta of Siberia (5). One of the major problems in the current studies of the lati-

 © Royal Swedish Academy of Sciences 2002 http://www.ambio.kva.se

tudinal treeline and related phenomena such as "timberline", etc. is the concept of "line". Most of the papers in this special Ambio Report recognize that these boundaries are not lines, but zones. The transition from taiga to tundra is often observed as a transition from forest, through an area dominated by forest in which patches of tundra occur, to tundra in which patches of forest occur, and then eventually to tundra without trees. Often there are east-west gradients related to the presence of a river valley, bogs, uplands, etc. which also confound the concept of a linear boundary and necessitate the application of a concept based on gradients of tree cover/density expressed on an area, not linear, basis.

Dynamics of the Boundary

In view of the uncertainties of defining and accurately locating the current location of the tundra-taiga boundary, it is not surprising that it is difficult to quantify changes in the location of the boundary over time. However, it is known that the tundra-taiga boundary is associated with the northern geographical limit of several tree species that have changed their distributions since the Last Glacial Maximum some 20 000 years ago (1). Much of the Russian Arctic was not glaciated in the Late Pleistocene and Holocene and it was partly forested. In western Siberia, newly deglaciated areas were colonized by trees as early as 15 000 to 13 000 years ago and about 10 000 years ago in northern Fennoscandia. At that time, pine was growing 500 m above its present altitudinal limit in northern Sweden and spruce was present there. During the last 6000 years in northern Fennoscandia and Eurasia, there has been a general cooling (about 2–4°C) and a southwards retreat of the treeline with change in species composition. Larch and birch retreated between 400 and 500 km during this period and spruce retreated then moved northwards to occupy its present position in Lapland only 2500 to 3000 years ago. The pattern of postglacial recovery in North America differed from that of Eurasia because most forest trees spread northwards from a large southern ice-free refugium in northwestern North America whereas part of the eastern Canadian Arctic was deglaciated more recently. Displacements of the North American treelines of up to 350 km have been reported but the data are uncertain and treeline movements in the region of 50 to 100 km are more likely with tree migration rates in the order of 0.2 to 0.4 km yr^{-1}, particularly in eastern Canada.

In view of the dynamic nature of the tundra-taiga boundary seen in the past, it is somewhat surprising that modern changes in the boundary associated with warming over the last century (ca 1°C per 10 years between 1965 and 1994 in some Arctic areas (6)) have rarely been reported. An exception is an increase in the treeline of 40 m during the 20th century in northern Sweden (7, 8), and an increase in shrub growth in Alaska (9). In fact, most of the changes in the location of the tundra-taiga boundary presented in this volume show a surprising displacement of the boundary to the south (3, 10). Part of this is a counter-intuitive repose to warming in which increasing oceanicity together with permafrost thawing and waterlogging have led to paludification and the death of treeline trees (2). In addition, human activities of various types, for example, mining, farming, forestry, have led to ecosystem degradation in the lesotundra (the Russian term for the tundra-taiga ecotone) zone and its southward displacement (3).

Predicting Future Changes in the Tundra-Taiga Zone and Their Implications

In order to model changes in the location and characteristics of the tundra-taiga ecotone, it is necessary to understand the causes of the treeline. Despite huge research efforts during the last 50 years, opinions on the causes of the treeline vary greatly. Some researchers see the limit of tree growth as a universal mechanism related to a specific process such as sink limitation (11, 12) or carbon limitation (13). Others see a range of possible physiological mechanisms that operate in different places and at different times (14). These physiological mechanisms are in turn affected by environmental factors such as incident radiation, temperature, wind, moisture, and soil nutrients, and result in impacts on tree reproduction, seedling establishment and the growth and physiology of mature trees. In addition, extreme conditions such as ice crystal abrasion that damages conifer needles and soil movement that displaces individuals, also directly damage treeline trees. Diseases, herbivory, pests, fires and human activities may also exert some control on the treeline at certain places and at certain times.

Models of vegetation redistribution resulting from global change operate on more general mechanisms such as biogeography and biogeochemistry (2, 4). Most current global vegetation models and regional models suggest that a major part of the tundra (up to approximately 30%) will be displaced by an advance of the boreal forest over the period in which atmospheric CO_2 will double (2). However, it is clear that this rate of forest migration has not yet been recorded even though temperature has risen dramatically in some areas. Also, most observations of the latitudinal treeline show a recent southern migration. In the Archangelsk region and the Komi Republic, the southern border of the lesotundra zone now lies 40 to 100 km further south than when previously surveyed. Human-derived tundra now covers about 470–500 000 km^2 of the lesotundra stretching from Archangelsk to Chukotka (3). Clearly, we need a new generation of models focussing on a wider range of processes in the North including land-use scenarios.

The changes in the extent and location of the tundra and taiga and the ecotone between will affect the feedbacks from the land surface to the atmosphere (15, 16). Using a state-of–the-art vegetation distribution model, BIOME 3, for current and 2 x CO_2 scenarios, changes in extent of the Scandinavian, Central Northern Siberian and Eurasian tundra areas were calculated as between 10% and 35% as a result of displacement by taiga (4). This process was calculated to significantly increase CO_2 drawdown and to significantly reduce CH_4 emissions with a net result in favor of carbon sequestration in the biosphere of a magnitude that would alter the radiative forcing of the Earth. However, while this negative feedback from biosphere to climate is occurring, a positive feedback will also operate. Earlier disappearance of snow from the tundra and a decrease in albedo of new areas of forest will lead to a significant heating of the lower atmosphere. This positive feedback could offset the negative feedback due to increased carbon sequestration (4). The transition from tundra to forest also affects evapotranspiration and the water storage capacity of the biosphere such that freshwater runoff *via* rivers to the Arctic Ocean may decrease (4).

Human activities also have impacts on the local climate of the lesotundra. Deforestation, as a result of industrial activities or forestry, increases wind speeds; pollution leads to earlier snowmelt and increased temperatures, and the northwards extension of farming and settlements in general induce permafrost thawing (3).

Monitoring Future Changes in the Tundra-Taiga Boundary

Much of the extensive tundra-taiga boundary is remote and accessible only with difficulty. Remote sensing from space-borne platforms is, therefore, likely to play a significant role in determining the dynamics of the tundra-taiga boundary (17). At a circumpolar scale, resolution between 30 and 100 m is probably the most feasible. At this scale, individual trees cannot be recognized. However, statistical parameters estimated from satellite images that record in the visible and near infra-red parts of the electromagnetic spectrum, or use radar techniques, have been applied successfully to treeline problems in the Russian Arctic

© Royal Swedish Academy of Sciences 2002
http://www.ambio.kva.se

(17). This technique has also been successfully applied to determine the extents of forest insect pest outbreaks (18), fires (19, 20), industrial pollution impacts (21–25) and reindeer overgrazing (26–30) in the lesotundra.

RECOMMENDATIONS FOR FUTURE RESEARCH

The complexity and great extent of the tundra-taiga ecotone, the uncertainties in its present location and characteristics, and our need to understand, predict and monitor changes in the ecotone require a circumarctic approach using generally agreed definitions and concepts, and standardized, measuring and experimental techniques. At its first meeting in Edinburgh in November 2000, the Steering Committee of the IASC project on the *Dynamics of the Tundra Taiga Boundary* outlined some approaches and measurements that should be made at locations throughout the circumarctic tundra-taiga ecotone (Table1). At its second meeting in Quebec in September 2001, the Steering Committee prioritized some activities that should be started as soon as possible (Fig. 1). We hope that members of the international research community will join our endeavours to understand and if possible protect the Earth's largest, but possibly most vulnerable, ecotone, and that the preceeding papers in this Ambio Report will provide a baseline for these activities.

Further information on the activities of the group can be found on the IASC web site: http:/www.iasc.no

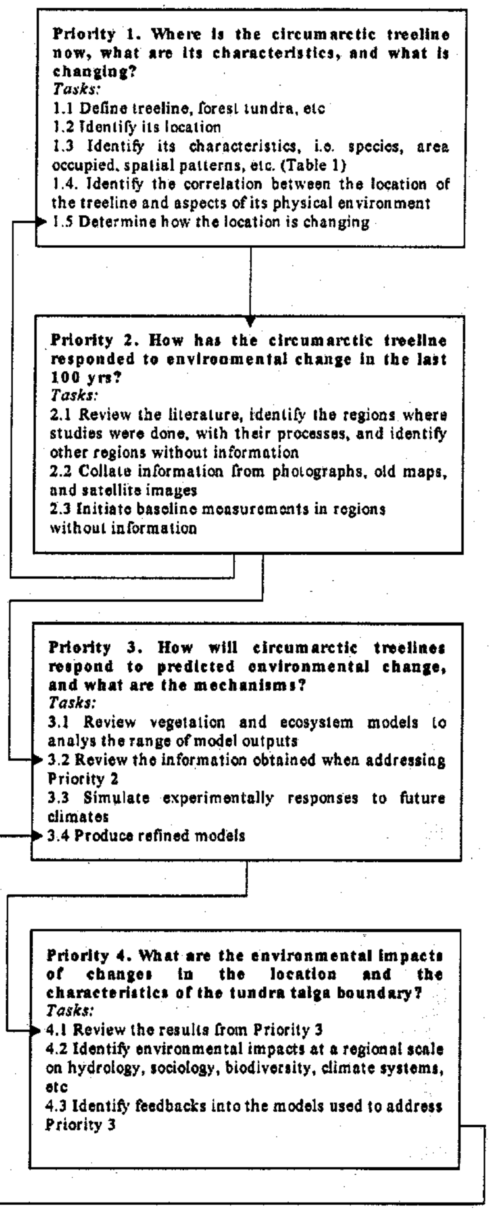
Table 1. Framework for standardized characterization and monitoring of the dynamics of the tundra-taiga interface. (Developed by the Steering Committee of the tundra-taiga project within the International Arctic Science Committee)

Location and characterization of the interface
Standardized GPS information
Mathematical representation of tree distribution patterns
Reference data sets from existing maps, photographs (terrain and aerial), satellite images and monitoring from digital photography to be initiated at sites.

Monitoring of biological parameters
Phenology of coniferous and deciduous trees
Growth (annual and retrospective)
Reproductive ecology
Biodiversity and abundance of trees, shrubs, understorey plants and animals
Plant-animal interactions
Human pressures
Disease of trees
Damage to trees by climate, fire, contaminants, etc.

Monitoring of physical parameters (these should also relate to existing programs such as the International Tundra Experiment and the Long Term Ecological Research Programme)
Snow characteristics and plant exposure during winter
Temperature
Wind speed
Humidity
Soil moisture and flooding
UV radiation
Fire interval
Solifluction
Radiation and energy characteristics

Figure 1. Research priorities and tasks identified by the IASC *Dynamics of the Tundra-Taiga*



References

1. Payette, S., Eronen, M. and Jasinski, P. 2002. Late Pleistocene and Holocene changes in the tundra-taiga interface. *Ambio Special Report 12*, 15–22.
2. Skre, O., Baxter, B., Crawford, R.M.M., Callaghan, T.V. and Fedorkov, A. 2002. How will the tundra-taiga interface respond to climate change? *Ambio Special Report 12*, 37–46.
3. Vlassova, T.K. 2002. Human impacts on the tundra-taiga zone dynamics: The case of The Russian Lesotundra. *Ambio Special Report 12*, 30–36.
4. Harding, R., Kuhry, P., Christensen, T.R., Sykes, M.T., Dankers, R. and Linden, S.vd 2002. Climate feedbacks at the tundra-taiga interface. *Ambio Special Report 12*, 47–55.
5. Callaghan, T.V., Werkman, B.R. & Crawford, R.M.M. 2002. The tundra-taiga boundary and its dynamics: concepts and applications. *Ambio Special Report 12*, 6–14.
6. Weller, G. 2000. The weather and climae of the Arctic. In: *The Arctic: Environment, People, Policy.* Nutall, M. and Callaghan, T.V. (eds). Harwood Academic Publishers, Reading, UK. pp 143–160.
7. Sonesson, M. and Hoogesteger, J. 1983. Recent tree-line dynamics (*Betula pubescens* Ehrh. ssp. *tortuosa* (Ledeb.) Nyman) in northern Sweden. *Nordicana 47*, 47–54.
8. Kullman, L. 1979. Change and stability in the altitude of the birch tree-limit in the southern Swedish Scandes 1915–1975. *Acta Phytogeogr. Suecica 65*, 1–121.
9. Sturm, M., Racine, C. and Tape, K. 2001. Climate change—Increasing shrub abundance in the Arctic. *Nature 411*, 546–547.
10. Crawford, R.M.M., Jeffree, C.E. and Rees, W.G. 2002. Paludification and forest retreat. *Ann. Bot.* (In press).
11. Körner, C. 1998. A re-assessment of high elevation treeline positions and their explanation. *Oecologia 115*, 445–459.
12. Körner, C. 1999. *Alpine Plant Life. Functional Plant Ecology of high Mountain Ecosystems.* Springer, Berlin, 338 pp.
13. Nojd, P. and Hari, P. 2001. The effect of temperature on the radial growth of Scots pine in northernmost Fennoscandia. *For. Ecol. Mgmt 142*, 65–77.
14. Sveinbjörnsson, B., Hofgaard, A. and Lloyd, A. 2002. The natural causes of the tundra - taiga boundary. *Ambio Special Report 12*, 23–29.
15. Betts, R.A. 2000. Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature 408*, 187–190.
16. Betts, R.A., Cox, P.M. and Woodward, F.I., 2000. Simulated responses of potential vegetation to doubled-CO2 climate change and feedbacks on near-surface temperature. *Global Ecol. Biogeogr. 9, 171–180.*
17. Rees, W.G., Brown, I.A., Mikkola, K., Virtanen, T. and Werkman, B.R. 2002. How can the dynamics of the tundra-taiga boundary be remotely monitored? *Ambio Special Report 12*, 56–62.
18. Høgda, K.A. and Tømmervik, H. 1998. Detection of caterpillar outbreaks in mountain birch forests. *Proc. 27th International Symposium on Remote Sensing of the Environment.* Information for Sustainability. June 8–12, 1998, Tromsø, Norway, pp. 532–534.
19. Bourgeau-Chavez, L.L., Harrell, P.A., Kasischke, E.S. and French, N.H.F. 1997. The detection and mapping of Alaskan wildfires using a spaceborne imaging radar system. *Int. J. Remote Sens. 18*, 355–373.
20. Li, Z., Nadon, S. and Cihlar, J. 2000. Satellite-based detection of Canadian boreal forest fires: development and application of the algorithm. *Int. J. Remote Sens. 21*, 3057–3069.
21. Tömmervik, H., Johansen, B.E. and Pedersen, J.P. 1995. Monitoring the effects of air-pollution on terrestrial ecosystems in Varanger (Norway) and Nikel-Pechenga (Russia) using remote-sensing. *Sci. Tot. Environ. 161*, 753–767.
22. Mikkola, K. 1996. A remote sensing analysis of vegetation damage around metal smelters in the Kola Peninsula, Russia. *Int. J. Remote Sens. 17*, 3675–3690.
23. Hagner, O. and Rigina, O. 1998. Detection of forest decline in Monchegorsk area. *Remote Sens. Environ. 63*, 11–23.
24. Toutoubalina, O.V. and Rees, W.G. 1999. Remote sensing of industrial impact on Arctic vegetation around Noril'sk, northern Siberia: preliminary results. *Int. J. Remote Sens. 20*, 2979–2990.
25. Saich, P., Rees, W.G. and Borgeaud, M. 2001. Detecting pollution damage to forests in the Kola Peninsula using the ERS SAR. *Remote Sens. Environ. 75*, 22–28.
26. Colpaert, A., Kumpula, J. and Nieminen, M. 1995. Remote Sensing: a tool for reindeer range land management. *Polar Record 31*, 235–244.
27. Kumpula, J., Colpaert, A. and Nieminen, M. 1995. Luontaisten syys—ja talvilaidunvarojen inventointi poronhoitoalella satelliittikuvien avulla: Laidunvarojen vaikutus poronhoitoon. (Natural late summer and winter pasture care inventory in a reindeer herding area with the help of satellite pictures: effect on reindeer herding of pasture care.). *Poromies 1*, 8–17. (In Finnish).
28. Johansen, B., Tømmervik, H. and Karlsen, S.R. 1996. Reinbeitene sett fra satellitt (Reindeer pastures seen from satellite). *Ottar 3*, 17–24. (In Norwegian).
29. Väre, H., Ohtonen, R. and Mikkola, K. 1996. The effect and extent of heavy grazing by reindeer in oligotrophic pine heaths in north-eastern Fennoscandia. *Ecogeography 19*, 245–253.
30. Mclaren, B.E. and Mahoney, S.P. 2001. Comparison of forestry-based remote sensing methodologies to evaluate woodland caribou habitat in non-forested areas of Newfoundland. *For. Chron. 77*, 866–873.

31. We thank all the participants of the "Dynamics of the Tundra-Taiga Boundary" workshop held at Abisko in April 2000 for their input to this process. We also thank all the authors of the articles included in this special issue of Ambio. The project would not have been possible without encouragement and funding from IASC, and Executive Secretary Odd Rogne in particular. The conference and publication were co-funded by the Royal Swedish Academy of Sciences, The Climate Impacts Research Centre of Kiruna, Sweden, and the Swedish Environmental Protection Agency as part of its contribution to the Arctic Climate Impacts Assessment (ACIA) process. We are grateful to all these organizations. The Abisko Scientific Research Station hosted the conference, and we thank its staff.