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*Published in:*
Ambio: a Journal of the Human Environment

*DOI:*
10.1579/0044-7447-33.7.469

2004



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# Synthesis of Effects in Four Arctic Subregions

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An assessment of impacts on Arctic terrestrial ecosystems has emphasized geographical variability in responses of species and ecosystems to environmental change. This variability is usually associated with north-south gradients in climate, biodiversity, vegetation zones, and ecosystem structure and function. It is clear, however, that significant east-west variability in environment, ecosystem structure and function, environmental history, and recent climate variability is also important. Some areas have cooled while others have become warmer. Also, east-west differences between geographical barriers of oceans, archipelagos and mountains have contributed significantly in the past to the ability of species and vegetation zones to relocate in response to climate changes, and they have created the isolation necessary for genetic differentiation of populations and biodiversity hot-spots to occur. These barriers will also affect the ability of species to relocate during projected future warming. To include this east-west variability and also to strike a balance between overgeneralization and overspecialization, the ACIA identified four major sub regions based on large-scale differences in weather and climate-shaping factors. Drawing on information, mostly model output that can be related to the four ACIA subregions, it is evident that geographical barriers to species re-location, particularly the distribution of landmasses and separation by seas, will affect the northwards shift in vegetation zones. The geographical constraints—or facilitation—of northward movement of vegetation zones will affect the future storage and release of carbon, and the exchange of energy and water between biosphere and atmosphere. In addition, differences in the ability of vegetation zones to re-locate will affect the biodiversity associated with each zone while the number of species threatened by climate change varies greatly between subregions with a significant hot-spot in Beringia. Overall, the subregional synthesis demonstrates the difficulty of generalizing projections of responses of ecosystem structure and function, species loss, and biospheric feedbacks to the climate system for the whole Arctic region and implies a need for a far greater understanding of the spatial variability in the responses of terrestrial arctic ecosystems to climate change.

## INTRODUCTION

The Arctic has become an important region in which to assess the impacts of current climate variability and amplification of projected global warming. This is because *i)* the Arctic has experienced considerable warming in recent decades (an average of about 3°C and between 4 and 5°C over much of the landmass), *ii)* climate projections suggest a continuation of the warming trend with an increase in mean annual temperatures of 4–5°C by 2080, *iii)* recent warming is already impacting the environment and economy of the Arctic and these impacts are expected to increase and effect also life style, culture, and ecosystems, and *iv)* changes occurring in the Arctic are likely to affect other regions of the Earth, for example changes in snow, vegetation, and sea ice are likely to affect the energy balance and ocean circulation at regional and even global scales (Chapter 1 in ref. 1). Responding to the urgent need to understand and project changes already occurring, and likely to occur in the Arctic, the Arctic Climate Impact Assessment (ACIA) (1) undertook a four-year study. Part of this study (2–9) assessed the impacts of changes in climate and UV-B radiation on terrestrial ecosystems.

The assessment of impacts on Arctic terrestrial ecosystems (2–9) has emphasized geographical variability in responses of species and ecosystems to environmental change. This variability is usually associated with a north-south gradient in climate, biodiversity, vegetation zones, productivity, and canopy height and complexity. It is clear, however, that significant east-west variability in environment and ecosystems is also important. Recent temperature trends show a general warming throughout the Arctic but some areas such as West Greenland have cooled recently (Chapter 2 in ref. 1) and plant distributions associated with altitudinal zones related to climate on mountains in the Faroe Islands have recently decreased in altitude because of a cooling trend (10). Also, latitudinal gradients in species diversity vary according to location and are best described as several parallel gradients, each of which depends on summer heat, but which vary from one geographical region to another (4). To include this variability and also to strike a balance between overgeneralization and overspecialization, the ACIA identified four major subregions based on large-scale differences in weather and climate-shaping factors (Chapter 1 in ref. 1). The subregions are presented in Figure 1. Each subregion has a unique geography that affects the present ecosystems and that will modify the possibilities for species, ecosystems and vegetation zones to relocate during projected climate warming.

This paper is a synthesis of the assessment of the impacts of changes in climate and UV-B radiation on Arctic terrestrial ecosystems (1–9, 11). This synthesis draws on information in the assessment that can be related to the four ACIA subregions. Most of the information is therefore based on model output. Details of the subregions are presented in Chapters 1 and 17 of the ACIA report (1) while details of the models that generate the climate and UV-B scenarios are presented in Chapters 3 and 4, respectively of the ACIA report (1). Many of the details relating to vegetation and carbon dynamics are derived specifically for this paper from the LPJ model (12), details of which are presented in Callaghan et al. (8). Other aspects of the assessment that cannot currently be divided into the subregions are summarized by Callaghan et al. (11).

**Table 1. Summary baseline information for the four subregions. Average and ranges (in brackets) of the drivers and responses of a leading Dynamic Global Vegetation Model, the LPJ model (12) to the forcing of outputs from four different climate models (CCC, GFDL, HadCM3, Echam4) run for the ACIA subregions (Chapter 4 in Corell (1)).**

| | **Region I** Arctic Europe, East Greenland, European Russian North and North Atlantic | **Region II** Central Siberia | **Region III** Chukotka, Bering Sea, Alaska, western Arctic Canada | **Region IV** Northeast Canada, Labrador Sea, Davis Strait, West Greenland |
|---|---|---|---|---|
| **Expected environmental changes** | | | | |
| Mean Annual Temperature from the ACIA Scenarios | | | | |
| Baseline 1980–1999 | -17 to 16°C | -8 to 4°C | -8 to 12°C | -20 to 12°C |
| 2020 (change from baseline) | -1 to 3°C | 0 to 2.5°C | -0.5 to 3°C | -1 to 4°C |
| 2050 (change from baseline) | -0.5 to 4°C | 0.5 to 4°C | 0 to 4°C | 0 to 7°C |
| 2080 (change from baseline) | 1 to 7°C | 1 to 6°C | 0.5 to 6°C | 0 to 8°C |
| Temperature change used for the LPJ Model (°C) | | | | |
| 2100–2000 | 3.9 (3.6–4.4) | 6.0 (5.4–7.5) | 4.4 (4.0–4.8) | 5.0 (4.5-5.5) |
| Precipitation (mm month$^{-1}$) | | | | |
| Baseline 1980–1999 | 10 to 150 mm | 10 to 70 mm | 10 to 150 mm | 5 to 130 mm |
| 2020 (change from baseline) | -10 to 12 mm | -8 to 5 mm | -10 to 8 mm | -10 to 20 mm |
| 2050 (change from baseline) | -20 to 20 mm | -2 to 5 mm | -4 to 12 mm | -8 to 35 mm |
| 2080 (change from baseline) | -20 to 25 mm | 0 to 10 mm | -3 to 12 mm | -15 to 35 mm |
| Precipitation change used for the LPJ Model (mm yr$^{-1}$) | | | | |
| 2100–2000 | 27.9 (-22.3–57.1) | 70.8 (21.4–116.4) | 36.9 (4.9–90.9) | 32.6 (-26.8-83.7) |
| UV-B change | | | | |
| Mean for 2010–2020 | 0 to 10% increase | 0 to 8% increase | 0 to 2% increase | 0 to 14% increase |
| Mean for 2040–2050 | 0 to 2% increase | 0 to 2% increase | 0 to 2% increase | 0-2% increase |
| **Ecosystem processes predicted by LPJ model** | | | | |
| NPP (Pg C yr$^{-1}$) | | See Table 1 in reference (7) for the total of the Arctic | | |
| 1960s | 1.2 | 4.0 | 4.6 | 1.5 |
| 2080s | 1.8 | 6.5 | 7.5 | 3.8 |
| % change | 46.3 | 62.3 | 63.8 | 144.4 |
| Change in C storage (Pg C) 2080–1960 | | See Table 1 in reference (7) for the total of the Arctic | | |
| Veg C | 0.2 | 1.7 | 2.5 | 1.3 |
| Soil C | -0.1 | 0.5 | 1.9 | 4.7 |
| Litter C | -0.02 | 0.5 | 1.8 | 3.4 |
| Total C | 0.04 (-0.7–0.8) | 2.8 (-0.9–7.1) | 6.2 (4.1-9.5) | 9.3 (6.5–14.0) |
| Change in albedo (due to vegetation change) | | | | |
| 2050++ | -0.1 to 0.05 | -0.05 to 0.025 | -0.1 to 0.025 | -0.05 to 0.025 |
| 2080++ | -0.1 to 0.01 | -0.05 to 0.025 | -0.1 to 0.025 | -0.1 to 0.025 |
| Landscape processes predicted by LPJ model | | | | |
| % change in areas of vegetation | | | | |
| Taiga v tundra** | | | | |
| 2020–1960 | 1.1 (-1.1–2.3) | 6.1 (4.2–8.6) | 4.2 (1.9-5.7) | 3.7 (2.9–4.4) |
| 2050–1960 | 3.2 (1.6–4.3) | 9.4 (7.5–10.2) | 8.2 (6.5-9.7) | 5.0 (3.8–6.2) |
| 2080–1960 | 5.0 (3.7–5.9) | 13.7 (11.1–17.3) | 11.9 (9.8-15.1) | 9.5 (6.8–12.5) |
| Polar desert v tundra*** | | | | |
| 2020–1960 | -2.3 (-3.1 – -1.1) | -6.9 (-11.0 – -3.9) | -5.3 (-10.8 - -2.4) | -12.7 (-23.0 – -7.2) |
| 2050–1960 | -3.5 (-4.8 – -2.7) | -9.9 (-13.2 – -7.7) | -11.0 (-15.7 - -8.9) | -23.6 (-33.5 – -16.3) |
| 2080–1960 | -4.2 (-5.9 – -3.2) | -11.4 (-14.6 – -10) | -13.2 (-16.6 - -11.4) | -35.6 (-47.8 – -25.9) |
| Biodiversity | | | | |
| No of rare endemic vascular plant species**** | 2 | 18 | 69 | 8 |
| Threatened vascular plant species (occurring at 1 unprotected location)**** | 1 | 4 | 11 | 0 |
| Threatened animal species***** | 2 | 4 | 6 | 1 |

* only a proxy as the change is derived from functional characteristics of the vegetation produced by the model rather than predictions of specific vegetation composition *per se*. For a proper vegetation distribution estimate it would be more appropriate to use a proper biogeographical model such as MIOME4.
** based on percentage increase in woody plants produced by LPJ.
***based on the percentage reduction in bare ground produced by LPJ.
**** extracted from (13)
*****(14)
++ (15) using IS92a scenario

## ENVIRONMENTAL CHARACTERISTICS

The four ACIA subregions (Fig. 1) differ greatly in their geography and climatology which leads to variation in future possibilities for the relocation of species and ecosystems, and differences in scenarios of future changes in climate and UV-B radiation (Table 1).

Geographically, zone IV has a far greater extent of land at high latitudes compared with other zones. This could potentially support northward migration of Arctic biota even if the Canadian high Arctic Archipelago and the glacial landscape of Greenland together with lack of suitable soils will, to some extent, pose problems to migration. Relatively narrow tundra zones in some parts of regions III and I could, under sea level rise and boreal forest expansion northwards, disappear with forest reaching the shore of the Arctic Ocean (Fig. 2 in Callaghan et al. (7)). Subregion I contains the relatively isolated high Arctic Islands of Svalbard, and the islands of Iceland and the Faroe Islands that might experience delayed immigration of southern species during warming. Both Iceland and the Faroe Islands have equivocal positions within classifications of the Arctic: the northern part of Iceland and the alpine zones of the Faroe Islands (10) have the strongest Arctic characteristics and climate warming can lead to altitudinal displacement of tundra-like vegetation in both areas, and displacement from the northern coastal area in Iceland. The imbalance of species loss and replacement by species invading more slowly to islands is expected to lead to an initial loss in diversity (16).

The 5 ACIA scenarios of temperature change show complex patterns with time, some from initial cooling to substantial warming. The data used for the modeling of vegetation zone displacement and carbon storage used a different baseline period (2000) than the ACIA scenarios (1980–1999) (1) and excluded the NCAR CSM. Also, the data for the LPJ model are cited for 2100, rather than 2080, as in the case of the ACIA scenarios (7). It is therefore difficult to compare the results, even though both approaches had four GCMs in common and used the same emissions scenario.

Changes in UV-B radiation are expected to vary among subregions, but only over the next 20 years. By 2050, stratospheric ozone repair is expected to reduce UV-B radiation to relatively low levels above present with no differences among subregions. Of course, this repair depends entirely on the success of management and regulation. In the near future however, UV-B increases are expected to be greatest in subregion IV, follow by I and II (17).

The projected shifts in thickness of the soils' active layer above the permafrost shows increases of 20–60% by 2071–2100 (compared to the IPCC baseline, 1961–1990). The largest percentage increases are in northern Siberia and the interior of the Alaska-Yukon Region. In general, the largest relative changes in the active layer occur in those regions where the active layer is presently shallow (Chapter 5 in ACIA (1)). Degradation of continuous to discontinuous permafrost and the disappearance of discontinuous permafrost will occur at the southern boundaries of each of the subregions.

## VEGETATION ZONES AND CARBON BALANCE

Region I, East Greenland, northern Fennoscandia, northwestern Russia, Svalbard, Iceland, and the Faroe Islands, includes many high Arctic areas but these are separated from terrestrial ecosystems of lower latitudes by barriers of open sea. The possibilities for future species relocation are limited, even though moderate warming is predicted here (Table 1). In contrast, Region II, Central Siberia from the Urals to Chukotka, has continuous landmasses from the tropics to the high Arctic. This region is currently warming, and scenarios show that future warming will be greater here than elsewhere. The possibilities for responses in ecosystem distribution, structure and carbon balance are therefore considerable. This is shown by large predicted increases in taiga which displaces tundra in particular, and also in decreases in polar desert, which is displaced to some extent by northwards movement of the tundra (Table 1). There is also a northwards displacement and reduction in prostrate dwarf-shrub tundra, particularly in Yakutsia and the Taymyr Peninsula together with a displacement of erect dwarf shrub tundra from much of the Russian Arctic by low and high-shrub tundra that expands markedly there (Fig. 2 in Callaghan et al. (2) and Fig. 2 in Callaghan et al. (7)). Region III, Chukotka, Alaska, and the western Canadian Arctic to the Mackenzie River, is an area with little high Arctic and large maritime influence. Increases in temperature and precipitation are expected to be moderate as are changes in vegetation (Table 1). Region IV, the central and eastern Canadian Arctic and West Greenland, is a region of fragmented landmasses that are often strongly glaciated or have recently become deglaciated. This area has experienced recent cooling, but a warming trend is expected over the period from the current time to 2100. Increases in temperature and precipitation are expected to lead to relatively small increases in taiga (compared with other subregions) but a particularly large loss of polar desert of about 36% by 2080.

In terms of carbon storage, all subregions are predicted to accumulate carbon, largely because of the replacement of bareground by tundra. Consequently, the greatest carbon gain is expected to occur in Region IV (Table 1; Fig. 3 in Callaghan et al. (7)). In contrast, the smallest gains – but still gains – are expected in Region I which has the smallest expected increase in temperature.

## BIODIVERSITY

Biodiversity is affected by habitat fragmentation. Scenarios of all projected human infrastructure development on Arctic flora and fauna suggest that these impacts in the Arctic extend for 4 – 10 km away from the infrastructure (18). This is a much wider zone of impact than in other regions of the earth. Nellemann et al. (18) calculated that 50% to 80% of the Arctic could be impacted by infrastructure development by 2050. Of course, infrastructure development varies among ACIA subregions and this remains to be characterized. However, threats to flora and fauna will be increased by the additive or even possible interactive effects of development of infrastructure and climate change.

The number of rare endemic vascular plant species in the Arctic varies greatly between the subregions (Table 1). Region I including the European Arctic has relatively little landmass and supports only 2 of the rare endemic vascular plant species. Region IV in West Greenland and Northeast Canada that contains a significant proportion of the high Arctic contains 8% of the species and central Siberia contains 18%. In complete contrast over 70% of the species are found in Beringia. 24 species are found on Wrangel Island (13). A recent modification (19) of the list of threatened Arctic plant species (CAFF Atlas of rare endemic vascular plants of the Arctic; 13) adds a further 63 plant species, but data have not yet been compiled on the ACIA subregional distributions. Although Table 1 shows clear subregional differences in the distribution of rare and endemic plant species, and also a surprisingly high number of these species, it should be born in mind that the taxonomic treatment of species is likely to vary from region to region and there is uncertainty about the taxonomic status of some of the species.

It is not clear to what extent the rarity of the species listed in Table 2 of Callaghan et al. (5) and Table 1 in this paper will be affected by climate change as many other factors determine rarity. However, the species concentrated in small areas such as Wrangel Island are particularly at risk from any future climate warming and species invasion.

The likely impacts of climate change on biodiversity in terms of threatened species require us to conceive new concepts of "threatened species" and "protection" of currently perceived threatened species (Fig. 1; Chapter 11 in ACIA et al. (1)). The numbers of species currently perceived as threatened vary between subregions. Subregion III contains significantly more rare plant species and threatened animal and plant species than other subregions. Although temperature and precipitation changes are likely to be less in this subregion than in others, the vulnerability of the biodiversity of this area is likely to be considerable. Northwards expansion of dwarf shrub and tree dominated vegetation into an area such as Wrangel Island that is rich in rare endemic species could result in the loss of many plant species. Although some of these might not be considered vulnerable because they are currently in "protected" areas, this protection is against local human activities such as hunting, infrastructure development, etc., and protection cannot extend to changes in climate and UV-B radiation. It is possible that some plant species, particularly outliers of more southerly distributions, might experience population expansion or reproduction and recruitment to populations leading to initial expansion in response to warming. However, displacement of herbaceous species by woody immigrants is a probability in the long term in mesic areas. In contrast to the possibility that some threatened species might proliferate in a warmer climate, some currently widespread species might become less abundant and even "threatened".

The greatest long-term threat to Arctic diversity is the loss of Arctic habitat (3). In locations where the tundra zone is narrow, boreal forest moves northward from the South and the ocean moves southward due to sea level rise, there is very likely to be, over a period of centuries, a loss of Arctic ecosystems and the species that characterize them.

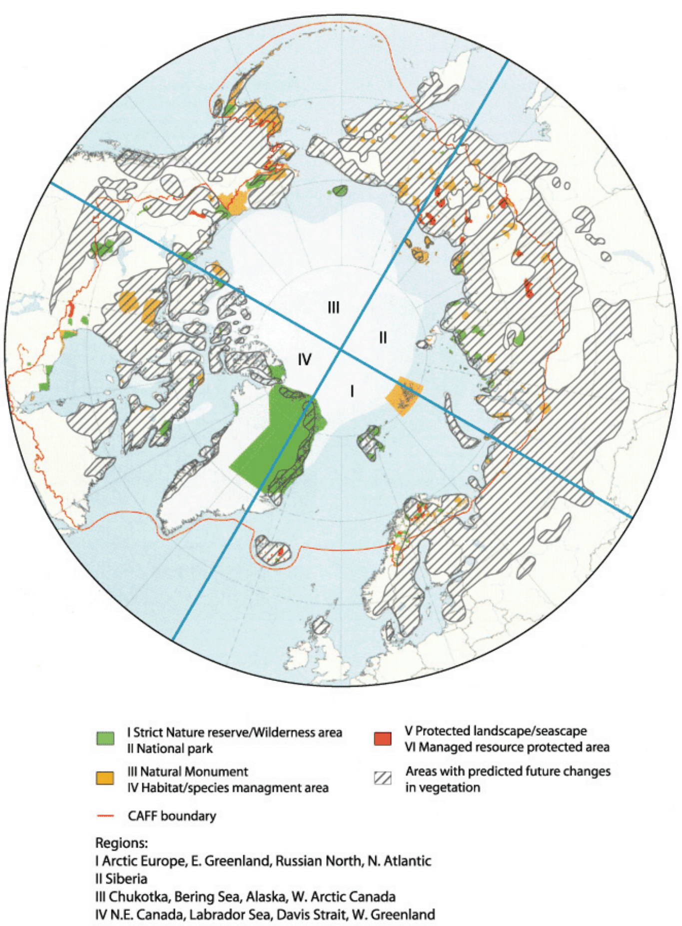


**Figure 1. Threats to current conservation using protected areas from climate change. A map of current protected areas in the Arctic (20) has been overlain by a map of changes in vegetation derived from Kaplan et al. (21) and Fig. 2 in Callaghan et al. (2) and Fig. 2 in Callaghan et al. (7).**

## CONCLUSIONS

North-South gradients in temperature dominate the geographical variability of species diversity, ecosystem structure and function, and carbon storage in the Arctic. However, these latitudinal patterns vary also longitudinally in relation to differences in geography, environmental history, and recent climate variability. Assessments of impacts of changes in climate and UV-B radiation within 4 subregions of the Arctic determined by large-scale differences in weather and climate-shaping factors, showed that geographical barriers to species relocation, particularly the distribution of landmasses and separation by seas, will affect the northwards shift in vegetation zones. The geographical constraints—or facilitation—of northward movement of vegetation zones will affect the future storage and release of carbon, and the exchange of energy and water between biosphere and atmosphere. In addition, differences in the ability of vegetation zones to relocate will affect the biodiversity associated with each zone while the number of species threatened by climate change varies greatly between subregions with a significant hot-spot in Beringiea. Overall, the subregional synthesis demonstrates the difficulty of generalizing projections of responses of ecosystem structure and function, species loss, and biospheric feedbacks to the climate system for the whole Arctic region and implies a need for a far greater understanding of the spatial variability in the responses of terrestrial arctic ecosystems to climate change.

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22. Acknowledgements. We thank Cambridge University Press for permission to reproduce this paper. Håkan Samuelsson kindly drafted Figure 1 and Jed Kaplan kindly provided the source material that was used to derive Figure 1. TVC and MJ gratefully acknowledge the grant from the Swedish Environmental Protection Agency that allowed them to participate in ACIA. We thank the participants, reviewers and particularly the leaders of the ACIA process for their various contributions to this study.

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