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Rationale, Concepts and Approach to the Assessment

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INTRODUCTION

A general recognition that the Arctic will amplify global climate warming, that UV-B radiation may continue to increase there because of possible delays in the repair of stratospheric ozone, and that the Arctic environment and its peoples are likely to be particularly susceptible to such environmental changes stimulated an international assessment of climate change impacts. The Arctic Climate Impacts Assessment (ACIA) is a four-year study, culminating in publication of a major scientific report (1) as well as other products. In this paper and those following in this Ambio Special Issue, we present the findings of the section of the report that focuses on terrestrial ecosystems of the Arctic, from the treeline ecotone to the polar deserts.

The Arctic is generally recognized as a treeless wilderness with cold winters and cool summers. However, definitions of the southern boundary vary according to environmental, geographical or political biases. This paper and the assessment in the following papers of this Ambio Special Issue focus on biota (plants, animals and microorganisms) and processes in the region beyond the northern limit of the closed forest (the taiga), but we also include processes south of this boundary that affect ecosystems in the Arctic. Examples are overwintering periods of migratory animals spent in the south and the regulation of the latitudinal treeline. The geographical area we have defined as the current Arctic is the area we use for developing scenarios of future impacts: Our geographical area of interest will not decrease under a scenario of the replacement of current Arctic tundra by boreal forests.

CHARACTERISTICS OF ARCTIC TUNDRA AND POLAR DESERT ECOSYSTEMS

The southern boundary of the circumpolar Arctic is the northern extent of the closed boreal forests. There is not a clear boundary but a transition from South to North consisting of the sequence: closed forest → forest with patches of tundra → tundra with patches of forest → tundra (2). The transition zone is relatively narrow (30–150 km) when compared with the forest and tundra zones in many, but not all, areas. Superimposed on the latitudinal zonation is an altitudinal zonation from forest to treeless areas to barren ground in some mountainous regions of the northern taiga. The transition zone from taiga to tundra stretches for more than 13 400 km around the lands of the Northern Hemisphere and is one of the most important environmental transition zones on Earth (3, 4), as it represents a strong temperature threshold close to an area of low temperatures. The zone has been called forest tundra, sub-Arctic and the tundra-taiga boundary or ecotone. Vegetationally, it is characterized as an open landscape with patches of trees that have low stature and dense thickets of shrubs that together with the trees totally cover the ground surface.

The environmental definition of the Arctic does not correspond with the geographical zone delimited by the Arctic Circle at 66.5°N latitude, nor political definitions. Cold waters in ocean currents flowing southwards from the Arctic depress the temperatures in Greenland and the eastern Canadian Arctic whereas the northwards flowing Gulf Stream warms the northern landmasses of Europe. Thus, at the extremes, polar bears and tundra are found at 51°N in eastern Canada, whereas agriculture is practiced beyond 69°N in Norway. Arctic lands span some 20° of latitude reaching 84°N in Greenland and locally, in eastern Canada, an extreme southern limit of 51°N.

The climate of the Arctic is largely determined by the relatively low angles of the sun to the Earth. Differences in photoperiod between summer and winter become more extreme towards the North. Beyond the Arctic Circle (66.5°N), the sun remains above the horizon at midnight on mid-summer's day and remains below the horizon at midday on midwinter's day.

Climatically, the Arctic is often defined as the area where the average temperature for the warmest month is lower than 10°C (5) but mean annual air temperatures vary greatly according to location, even at the same latitude. They vary from –12.2°C at Point Barrow, Alaska (71.3°N) to –28.1°C at the summit of the Greenland ice sheet (about 71°N) (6) and from 1.5°C at 52°N in sub-Arctic Canada to 8.9°C at 52°N in temperate Europe. The summer period progressively decreases from about 3.5 to 1.5 months from the southern boundary of the Arctic to the North, and mean July temperature decreases from 10–12°C to 1.5°C. In general, precipitation in the Arctic is low, decreasing from about 250 mm in the South to as low as 45 mm per year in the polar deserts of the north (7), with extreme precipitation amounts in maritime areas of the sub-Arctic, for example 1100 mm at 68°N in Norway. However, the Arctic cannot be considered to be arid because of low rates of evaporation: even in the polar deserts, air humidity is high and the soils are moist during the short growth period (8). The word "desert" refers to extreme poverty of life.

The Arctic is characterized by the presence of continuous permafrost, although there are exceptions such as the Kola Peninsula. Continuous, and deep (more than 200 m) permafrost is also characteristic south of the treeline in large areas of Siberia that reach to Mongolia. The depth of the soil's active layer during the growing season depends on summer temperatures and varies from about 80 cm close to the treeline to about 40 cm in polar deserts. However, active layer depth varies according to local conditions within landscapes according to topography: it can reach 120 cm on south-facing slopes and be as little as 30 cm in bogs, even in the South of the tundra zone. In many areas of the Arctic, continuous permafrost becomes deeper and degrades into discontinuous permafrost in the South of the zone. Active layer depth, decreases in the extent of discontinuous permafrost and coastal permafrost will be particularly sensitive to climatic warming. Permafrost and active layer dynamics lead to patterning, such as polygons, in the landscape. Topography plays an important role in defining habitats in terms of moisture and temperature as well as active layer dynamics (9, 10) so that Arctic landscapes are a mosaic of microenvironments. Topographic differences of even a few tens of cm are important for determining habitats, for example polygon rims and centers, whereas greater topographical differences of meters to tens of meters determine wind exposure and snow accumulation which in turn affect plant communities and animal distribution (11). Topographical differences become more important as latitude increases.

Ecosystem disturbances are characteristic of the Arctic. Mechanical disturbances include thermokarst through permafrost thaw, freeze-thaw processes, wind, sand and ice-blasts, seasonal ice oscillations, slope processes, snow load, flooding during thaw, changes in river volume and coastal erosion and flooding. Biological disturbances include insect pest outbreaks, peaks of grazing animals that have cyclic populations, and fire. These disturbances operate at various geographical and time scales (Fig. 1) and affect the colonization and survival of organisms and thus ecosystem development.

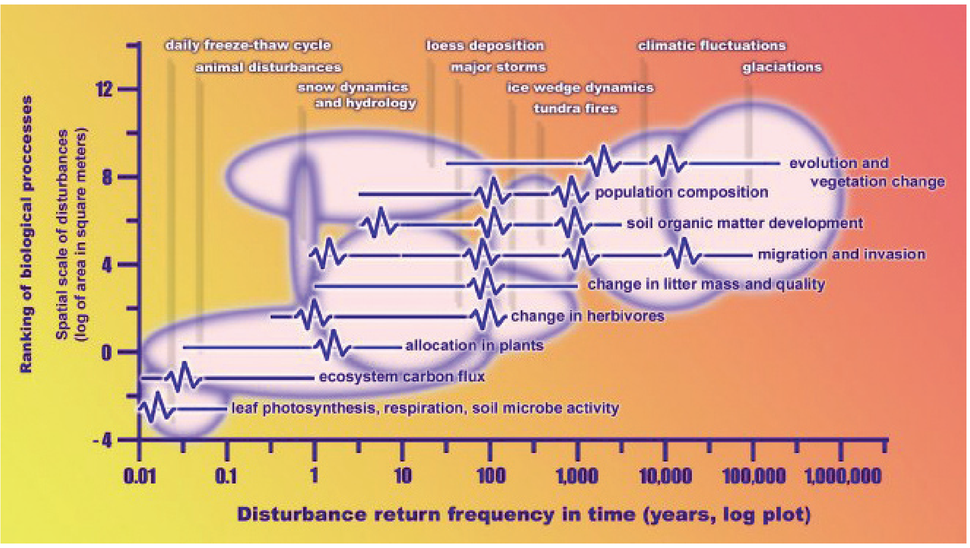

Figure 1. Schematic timescale of ecological processes in relation to disturbances in the Arctic. The schematic does not show responses expected due to anthropogenic climate change (based on Forbes et al. (30), Oechel and Billings (50), Shaver et al. (51)).

Arctic lands are extensive beyond the northern limit of the tundra-taiga ecotone where, according to the classification of Bliss and Matveyeva (12) they amount to about 7 567 000 km^2. They cover about 2 560 000 km^2 of the former Soviet Union and Scandinavia, 2 480 000 km^2 in Canada, 2 167 000 km^2 in Greenland and Iceland, and 360 000 km^2 in Alaska (12). Figure 2, which is based on a classification of Walker (13) and mapped by Kaplan et al. (14), shows the distribution of Arctic and other vegetation types (this can be compared with a recent vegetation map; 15). The distribution of Arctic landmasses is often fragmented: seas separate large Arctic Islands (Iceland, the Faroe Islands, Svalbard, Novaya Zemlya, Severnaya Zemlya, New Siberian Islands, Wrangel Island, etc.) and the landmasses of the Canadian Archipelago and Greenland. Similarly, the Bering Strait separates the Arctic lands of the Old and New Worlds. Large mountains such as the East-West running Brooks Range in Alaska and the Putorana Plateau in Siberia separate tundra and taiga. Such areas of relief contain outposts of boreal species on their southern major slopes that could potentially expand northwards and areas that could act as refuges for arctic-alpine species at higher elevations. The Taymyr Peninsula is the only continuous landmass that stretches for 900 km from the northern tundra limit to taiga without geographical barriers to the dispersal of animals and plants (16). The width of the tundra zone varies greatly in different parts of its circumpolar stretches. On average, it does not exceed 300 km, but in some regions (e.g. the lower reaches of the Kolyma River) the tundra zone extends only 60 km from treeline to coast. In such areas, the tundra zone is potentially highly vulnerable to climate warming.

The vegetation of the Arctic varies from forest tundra in the south where plant communities have all the known plant life forms for the Arctic, and have continuous canopies in several layers extending to more than 3 m high, to polar deserts in the North where vegetation colonizes 5% or less of the ground surface, is less than 10 cm high, and is dominated by herbs, mosses and lichens (Fig. 3). Species richness in the Arctic is low and decreases towards the north: there are about 1800 species of vascular plants, 4000 species of cryptogams, 75 species of terrestrial mammals, 240 species of terrestrial birds, 3000 species of fungi, 3300 species of insects (13, 17) and thousands of prokaryotic species (bacteria and archaea) whose diversity in the tundra has only recently begun to be estimated (11). However, the Arctic is an important global pool of some groups such as mosses, lichens, and springtails (and insect parasitoids; H. Roininen, unpubl.) because their abundance here is higher than in other biomes. Net primary production, net ecosystem production and decomposition rates are low (18). Food chains are often short and typically there are few representatives at each level of the chain (2). Arctic soils are generally shallow and underdeveloped with low productivity and immature humus of the *moor*-type (9). Substantial heterogeneity of the soil cover due to numerous spatial gradients has an important influence on the microtopographical distribution of the soil biota (invertebrates, fungi, bacteria) which can potentially amplify (exacerbate) any negative effects of climatic changes.

The Arctic has a long history of human settlement and exploitation based initially on its rich aquatic biological resources and more recently on its minerals and fossil hydrocarbons. At the end of the last glacial stage, people migrated from the Old World to the New across the ice-free Bering land bridge and along its southern coast (ca. 14 000–13 500 years BP) (19). As early as ca. 12 200 years BP, areas north of the Fennoscandian ice sheet in northern-

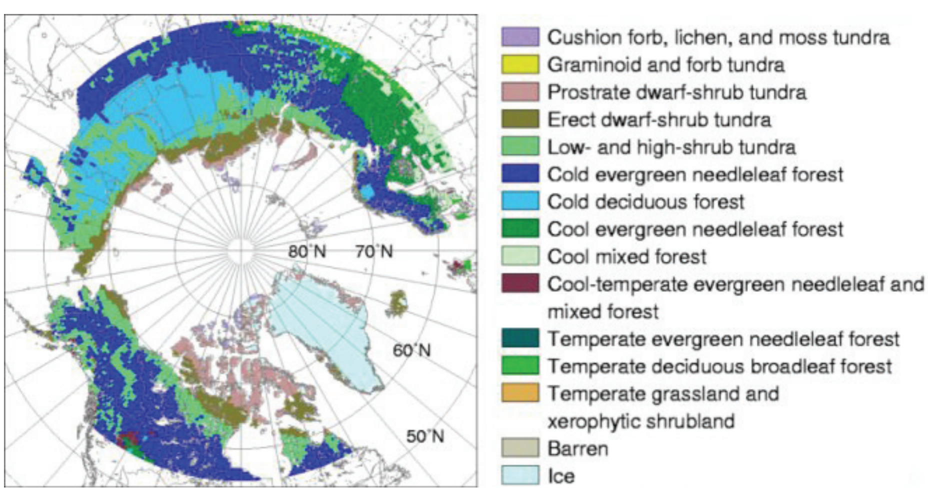

Figure 2. Present day natural vegetation of the Arctic and neighboring regions from floristic surveys. Vegetation types 1–5 are classified as Arctic, whereas types 6–8 are classified as boreal forest (modified from Kaplan et al. (14)).

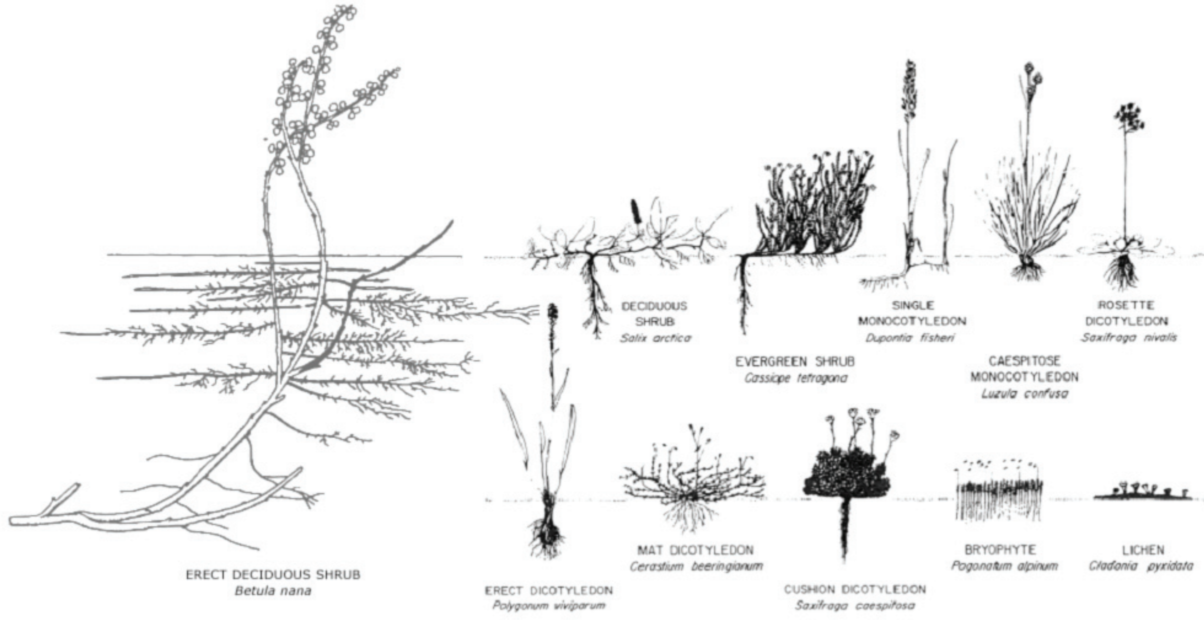

Figure 3. Growth forms of Arctic plants (modified from Webber et al. (10)).

most Finnmark, Norway, had been settled (20). Even earlier palaeolithic settlements (ca. 40 000 years BP) have been recorded from the eastern European Arctic (21). The impacts these peoples had on terrestrial ecosystems are difficult to assess but were likely to be small given their hunter–gatherer way of life and small populations. The prey species hunted by these peoples included the megafauna, such as the woolly mammoth, which became extinct. The extent to which hunting may have been principally responsible for these extinctions is a matter of continuing debate (22) but this possibility cannot be excluded (23). It is also uncertain to what extent the extinction of the megafauna may have contributed to, or been at least in part a result of, the accelerated northward movement of trees and shrubs, and consequent changes in vegetation structure (see ref. 2 and references therein). Although estimates of the population density of megafaunal species are fraught with uncertainties, it seems unlikely that these species were sufficient to constrain the spread of woody taxa in response to favorable environmental change.

During the last 1000 years, resources from terrestrial ecosystems have been central to the mixed economies of Arctic regions: many inland indigenous communities still derive most of their protein from subsistence activities such as caribou hunting (24). During this period, increasing trade between peoples of temperate latitudes and Arctic indigenous peoples is likely to have affected a few target animal species such as the reindeer, which was domesticated in Fennoscandia and Russia, ermine hunted for fur, and birds of prey used for hunting as far away as the eastern Mediterranean lands. However, the most dramatic impacts occurred after World War II through exploitation of minerals and oil, and fragmentation of the Arctic landscape by infrastructure (25). Vlassova (26) suggests that industrial activities and forestry have displaced the Russian forest tundra southwards by deforesting 470 000 to 500 000 km^2 of lands that now superficially resemble the tundra. Although this estimate has been challenged as greatly exaggerated (because northern taiga areas have been included in forest tundra), such effects occur locally in the Yamal Peninsula and a need for a re-appraisal has been highlighted. Therefore, we have only limited knowledge of the possible past interactions between people and their environment that could have shaped the ecosystems we see today. This knowledge shows, however, that any future increases in population density and human activity could modify expected future responses of Arctic ecosystems to changes in climate and UV radiation.

RAISON D'ÊTRE FOR THE ASSESSMENT

The Arctic is experiencing dramatic environmental changes which, for many reasons, are likely to have profound impacts on Arctic ecosystems. Among the biomes of the world the Arctic is outstanding in that the dominance of climate change amongst the major factors affecting biodiversity (27). Also, the Arctic biota of the present day are relatively restricted in range and population size compared with their Quaternary history (28). When the treeline advanced northward during the warming of the early Holocene, a lowered sea level allowed a belt of tundra to persist around the Arctic basin, whereas any future northward migration of the treeline will further restrict the area of tundra because sea level is expected to rise. Arctic ecosystems are known to be vulnerable to current disturbances (29–31) and to have long recovery times: e.g. sub-Arctic birch forest defoliated by insects can take 70 years to recover (32). Current and predicted environmental changes are likely to add additional stresses and to decrease the potential for ecosystem recovery from natural disturbances while providing thresholds for shifts to new states, for example when disturbances open gaps for invasion of species new to the Arctic.

Changes in Arctic ecosystems and their biota are important to the peoples of the Arctic in terms of food, fuel and culture and potentially could have global impacts because of the many linkages between the Arctic region and those regions further south. Several hundreds of millions of birds migrate to the Arctic each year and their success in the Arctic determines their roles at lower latitudes (11). Physical and biogeochemical processes in the Arctic affect atmospheric circulation and the climate of regions beyond the Arctic (33). We know that ecosystems have responded to past environmental changes in the Arctic, we also know that current environmental changes are occurring (6, 34, 35). This understanding indicates that there will be future responses of Arctic ecosystems and species to expected future and ongoing changes in climate (36). We also know that current levels of UV-B radiation, as well as higher levels, can affect sub-Arctic plants (37–39). Arctic plants may be particularly sensitive to increases in UV-B radiation because UV-B damage is not dependent on temperature whereas enzyme-mediated repair of DNA damage could be constrained by low temperatures (40–43).

For all these reasons, we need to understand the relationships between ecosystems and the Arctic environment. Although many aspects of the Arctic environment are changing concurrently, e.g. climate, pollution, atmospheric nitrogen deposition, atmospheric concentrations of carbon dioxide, UV-B radiation and land use, the specific mission of this and the following papers in this Ambio Special Issue is to focus on impacts of changes in climate and UV-B radiation on Arctic terrestrial ecosystems and their species and processes.

RATIONALE FOR THE STRUCTURE OF THE SPECIAL ISSUE

The effects of climate are specific to species, age/developmental stages of individuals and processes from metabolism to evolution (Fig. 1). Although there are many ways in which to organize an assessment of climate and UV-B impacts, throughout this Ambio Special Issue we follow a logical hierarchy of increasing organizational biological complexity to assess impacts on species, the structure of ecosystems, the function of ecosystems, and landscape and regional processes. A basic understanding of biological processes related to climate and UV-B radiation is required before we can assess impacts of *changes* in climate and UV-B on terrestrial ecosystems (44). Consequently, the structure of the Special Report progresses from a review of climate and UV controls on biological processes to an assessment of potential impacts of changes in climate and UV-B on processes at the species and regional levels. Some effects of climate change on ecosystems may be beneficial to people, while others may be harmful.

The changes in climate and UV-B that we use to assess biological impacts are of 2 types: *i)* those already documented; and *ii)* those established from scenarios of UV-B and climate derived from Global Climate Models (GCMs) (1). We know that mean annual and seasonal temperatures have varied considerably in the Arctic since 1965 (6). Western parts of North America and central Siberia have warmed by about 1.25°C (mean annual temperature and up to 2°C in winter) per decade while West Greenland and the eastern Canadian Arctic have cooled to the same extent.

Fennoscandia has seen little warming (about 1°C in the West to almost 0°C in the East (45)) over the past century. Precipitation has also changed. The duration of the snow-free period at high northern latitudes has increased by 5–6 days per decade and the week of the last observed snow cover in spring has become earlier by 3–5 days per decade over the period 1972–2000 (34). Stratospheric ozone has been depleted over recent decades, for example by a maximum of 45% below normal in the high Arctic in spring (35). This has probably led to an increase in UV-B radiation reaching the Arctic's surface, although the measurement period is short (O. Engelsen and G. Hansen, unpubl. data). Scenarios of future changes suggest that mean annual temperatures could continue to increase in the Arctic by 2 to 5°C (46) and that UV-B radiation in spring could increase by 20–90% in April in much of the Arctic by 2010–2020 (47). A detailed authoritative assessment of recent and projected changes in climate and UV-B radiation is presented in Correll (1). Our assessment of the impacts of these changes on terrestrial ecosystems has been based on existing literature rather than new research or modeling activities within the ACIA assessment. Consequently, the scenarios of climate/UV-B changes that existing long-term experimental manipulations of temperature and/or UV-B radiation were based on at their outset relied on earlier scenarios of change (48). However, we use the most recent scenarios to provide a context for our assessment, and to modify our predictions of ecosystem responses to earlier scenarios where appropriate. We also use the ACIA climate scenarios (1) directly to illustrate the responses of some species to projected climate changes.

APPROACHES USED FOR THE ASSESSMENT: STRENGTHS, LIMITATIONS AND UNCERTAINTIES

In the following papers in this Ambio Special Issue, we assess information on interactions between climate/UV-B radiation and ecosystems based on a wide range of sources derived from experimental manipulations of ecosystems and environments in the field; laboratory experiments; monitoring and observation of biological processes in the field; conceptual modeling using past relationships between climate and biota (paleo-analogs), and current relationships between climate and biota in different geographical areas (geographical analogs) to infer future relationships; and process-based mathematical modeling. Where possible, we include indigenous knowledge (limited to published sources) as an additional source of observational evidence.

We recognize that each method has uncertainties and strengths (49). By considering and comparing different types of information we hope to have achieved a more robust assessment. However, the only certainties of our assessment are that there are various levels of uncertainty in our predictions and that even if we try to estimate the magnitude of these, surprise responses of ecosystems and their species to changes in climate and UV-B radiation are certain to occur.

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