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 midsummer’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 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 Matveeva (12) they amount to about 7 567 000 km². They cover about 2 560 000 km² of the former Soviet Union and Scandinavia, 2 480 000 km² in Canada, 2 167 000 km² in Greenland and Iceland, and 360 000 km² 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 north-
most Finnmark, Norway, had been settled (20). Even earlier pa-
laeolithic 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 pop-
ulations. 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 respon-
sible 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 move-
ment 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 ecosys-
tems 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 domes-
ticated in Fennoscandia and Russia, ermine hunted for fur, and
birds of prey used for hunting as far away as the eastern Medi-
terranean lands. However, the most dramatic impacts occurred after
World War II through exploitation of minerals and oil, and frag-
mentation 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 km² 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 popula-
tion 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 vul-
nerable 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 link-
ages 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 respond-
ed 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, atmos-
pheric 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 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.

References and Notes
