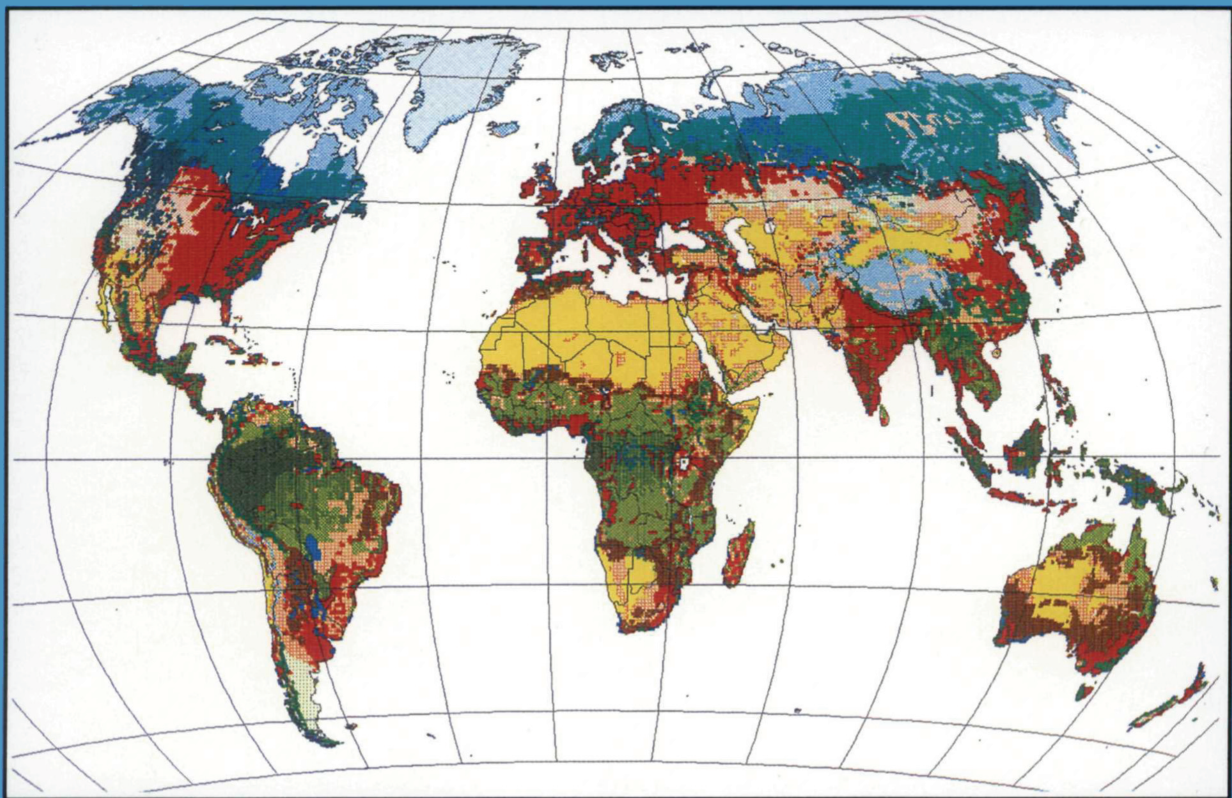
Impacts of Climate Change on Ecosystems and Species: Implications for Protected Areas



IVth World Congress on National Parks and Protected Areas
Caracas, Venezuela

IUCN
The World Conservation Union

Impacts of Climate Change on Ecosystems and Species: Implications for Protected Areas

IVTH WORLD PARKS CONGRESS

A World Congress on National Parks and Protected Areas had been held each decade since 1962. The objective of the Congress process is to promote the development and most effective management of the world's natural habitats so they can make their optimal contribution to sustaining human society. The IVth World Congress, held in Caracas, Venezuela, 10-21 February 1992, aimed to reach out to influence numerous other sectors, beyond those professionals directly concerned with protected areas. Management Agencies, non-governmental conservation organisations, traditional people's groups, relevent industries and resource were brought together and involved to enhance the role of protected areas in sustaining society, under the theme "Parks for Life".

RIVM - RUKSINSTITUUT VOOR VOLKSGEZONDHEID EN MILIEUHYGIENE

The National Institute of Public Health and Environmental Protection (RIVM) is the key reference institute of the Netherlands Ministry of Housing, Physical Planning and Environment in the area of climate change and other global environmental problems. One of the core activities of the RIVM is to describe the state of the environment and the future environmental quality at the national, European and global levels under various scenarios.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

The Climate Change Division in the Office of Policy Analysis at the US Environmental Protection Agency is responsible for projects supporting the inplementation of the Framework Convention on Climate Change and the US Climate Change National Action Plan.. Topics covered include the effects of climate change; methods for assessing greenhouse gas sources and sinks; benefiits generated by preventing, or adapting to, climate change; and policies for the reduction of greenhouse gases.

WWF - WORLD WIDE FUND FOR NATURE

WWF - World Wide Fund for Nature is the world's largest private international conservation organisation with 28 Affiliate and Associate National Organisations around the world and over 5.2 million regular supporters. WWF aims to conserve nature and ecological processes by preserving genetic, species and ecosystem diversity; by ensuing that the use of renewable natural resources is sustainable both now and in the longer term; and by promoting actions to reduce pollution and wasteful exploitation and consumption of resources.

THE MARINE AND COASTAL AREAS PROGRAMME

IUCN's Marine and Coastal Areas Programme was established in 1985 to promote activities which demonstrate how conservation and development can reinforce each other in marine and coastal environments; conserve marine and coastal species and ecosystems; enhance awareness of marine and coastal conservation issues and management; and mobilise the global conservation community to work for marine and coastal conservation. The Marine Conservation and Development Reports are designed to provide access to a broad range of policy statements, guidelines, and activity reports relating to marine issues of interest to the conservation and development community.

Impacts of Climate Change on Ecosystems and Species: Implications for Protected Areas

Edited by John Pernetta, Rik Leemans, Danny Elder and Sarah Humphrey

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Editorial preface

The papers contained in this volume are concerned with management issues arising from the anticipated impacts of global climate change and sea level rise on ecosystems and species. They form a logical development of the issues discussed in volumes two and three, which in turn are based on the modelling and policy considerations covered in the contributions to volume one of this series. This collection of papers was presented to a workshop on the implications of climate change and sea level rise for national parks and protected areas, convened at the IVth World Parks Congress held in Caracas, Venezuela, in January 1992.

The two papers by Solomon and Buddemeier represent synoptic overviews based on commissioned reviews and the deliberations of the Symposium on the Impacts of Climate Change on Ecosystems and Species, held in Amersfoort in December 1991. The paper by Solomon outlines the various scientific and management issues that are applicable to different eco-climatic regimes. It will be clear to the reader that the issue of uncertainty concerning future patterns of precipitation in time and space is a major constraint to developing scenarios of future vegetation distribution patterns in the twenty first century and beyond. The review by Buddemeier, concentrating as it does on a single marine ecosystem type, namely coral reefs, emphasises the importance of considering short-term stresses against the background of longer term climate change. This is a recurring theme in papers contained in the other volumes. From a perspective of the continued survival and conservation of reef ecosystems, Buddemeier suggests that various factors such as remoteness, variety, size, and recolonisation potential should be incorporated into any consideration of the establishment of future parks and protected areas.

A different approach is adopted by Taylor and Hamilton in their paper on the impacts of climatic change on tropical forests in Africa. Through a careful review of past climatic changes and influences on tropical forests systems in that continent, they suggest that the survival of forest ecosystems would not be seriously threatened by predicted climatic changes. They caution however, that the past responses of forest ecosystems may not be a guide to the future, since such changes occurred in the absence of significant levels of human influence and interference. They conclude that the present distribution of African forest reserves may be inadequate to provide future protection to some types of forest system. There is therefore an urgent need to protect areas which are believed to have been climatically more stable in the past and which are currently rich in both absolute number of species and number of endemic species.

The contributions of de Groot and Ketner, and Herman and Scott provide different approaches to the problems of managing species and ecosystems in the face of climatic change. De Groot and Ketner discuss the climate sensitivity of species and ecosystems in northwestern Europe and the way in which such an assessment could be used to determine priorities for future conservation action. They emphasise the need for long-term monitoring and trend analysis; for modelling; for research in phenology and demography; and, for approaches which include both integrated multi-disciplinary landscape studies and laboratory experiments. Herman and Scott discuss a detailed method of assessing the vulnerability to climate change of vertebrates at regional and local levels using the example of Nova Scotia. The principles involved in developing this system could be applied to any group of species in any location and the described method makes allowance for the absence of data or information concerning individual species potential responses.

In their review of the impacts of climate change on mountain protected areas and implications for management, Peine and Martinka emphasise the potential value of montane ecosystems as indicators or early warning systems of biological responses to climate change. They advocate the establishment of a global network of montane monitoring stations in protected areas; and suggest how the sensitivity of montane ecosystems to climate change could be assessed and used in developing strategic plans for species conservation.

The papers in this volume provide a wide variety of approaches to sensitivity and vulnerability analysis, highlighting the current need to develop globally applicable methodologies, if global objectives, such as the maintenance of biodiversity at genetic, species and ecosystem levels, are to be achieved. Whilst it might appear on first reading that these papers provide little concrete advice for managers concerning the day-to-day management of parks and protected areas, there is nevertheless a wealth of ideas contained in the contributions to this volume.

The difficulty facing ecologists and conservation scientists in providing advice for future management and policy directions, reflects the present "state-of-the-art". Physical models of future climates and sea level conditions at a regional or local level have great uncertainty. The development of impact statements or scenarios of the future distribution and status of ecosystems is therefore even more uncertain. On the basis of these "uncertain" future environmental conditions and biological responses, ecologists are expected to provide sound, practical advice to decision makers concerning alternative courses of immediate action.

Where uncertainty reaches the level which it clearly does in terms of predicting the future status of an individual national park or protected area in the year 2050 or 2100 then ecologists are forced to hide their ignorance behind a curtain of "ifs and buts, and maybes". The automatic recourse of a scientist under such circumstances is to say "we need more information therefore decision makers should fund more monitoring". A number of papers in this volume advocate courses of action to improve the knowledge and databases which currently exists. What these papers also clearly indicate is that there are indeed courses of action which should be adopted now that would greatly enhance the conservation of natural resources and global biodiversity in the face of the long-term threats from global climate change and sea level rise.

The underlying philosophy which forms the foundation on which are based national and international efforts in the field of nature protection and conservation is, that humanity must act now to conserve the maximum potential of the world's natural resources and environment for the use and enjoyment of future generations. The establishment of national parks and protected areas provides one strategic course of action to achieve this objective. Regrettably the background on which such protected areas have been established in the past is one of constancy or stability of the natural environment. The Villach Conference in 1985 agreed that the use of past climate as a reliable guide to the future was no longer a tenable position for planning future human development and use of resources. Clearly then, there exists a pressing need to adopt and incorporate the concepts of environmental change into the planning and management of parks and protected areas. Not only has the concept of static, "no-go" areas been overtaken by the needs and aspirations of humanity, but it is now outdated and outmoded when considered against a framework of dynamic, changing environmental conditions.

The future of parks and protected areas lies therefore in a multi-disciplinary, multi-use, flexible approach to the conservation of biodiversity and resources (both actual and potential). A static approach, will ultimately result in protected areas being over-taken by events, they may well exist in areas no longer suitable for the maintenance of the species and ecosystems they were originally designed to conserve. The challenge for conservation biologists is therefore to develop the guidelines and management strategies which will provide a blueprint for conservation in a changing world. Whilst this volume makes no pretence to provide such a "blueprint" it does provide some ideas and suggestions for the way in which we should look at managing parks and protected areas for the twenty first century.

J.C. Pemetta,
April 1993

Management of terrestrial parks and reserves during climate change

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Introduction

Warming of the lower atmosphere as a consequence of the gradual increase since about 1850 in concentration of atmospheric greenhouse gases (GHGs) has been predicted. In addition to the most common of the GHGs, CO_2, concentrations of other radiatively active gases such as methane, CFCs and ozone are now clearly increasing. Coincidentally, the globe has warmed measurably during the past 100 years. Indeed, the eight warmest years of the past century have been experienced in the past 12 years (Kerr, 1992). Changes in precipitation regime are not as predictable. Warming should increase rainfall as a result of increased evaporation rates. The enhanced evaporation should also increase drying. Whether the new balance of rainfall and evaporation will result in a dryer or a wetter world is not known. Increased rainfall could still produce terrestrial drought as much of the enhanced rainfall may occur over the oceans and the increased evaporation could characterise continental regions. At the very least, important changes in rainfall patterns are likely to be induced by global warming.

The response of biotic communities and populations to greater warmth and uncertain moisture changes will be of critical importance to planners and managers (stewards) of parks and nature reserves. In contrast to the emerging picture of a rapidly changing world, most parks are designed and maintained on the assumption of environmental stability, and many have been established to preserve specific biotic communities in perpetuity. Yet, the organisms and communities in parks which are adapted to local environments may be unable to function outside relatively narrow ranges of temperature and precipitation.

This review concentrates on plants rather than animals because individual plants cannot respond to climatechange by moving to more favorable locations. Even this generalisation may not apply in the case of some animal populations where barriers to dispersal occur. For example, the moose living on Isle Royale National Park, Michigan, at the southern edge of their geographic range, simply cannot breathe fast enough to dissipate their excess heat during the warmest summers there and the population is likely to disappear from the island after a succession of warm summers. Responses of other organisms or communities may be more subtle, but the consequences may be even more disastrous to parks managed on the concept of environmental stability. For example, the demise of a dominant tree species may produce a new sunlight regime, modifying the competitive relationships among remaining plants, opening the biotic community to invasion by exotic or unwanted species, and changing the community structure for long time periods.

To plan and manage nature reserves and parks in a world of rapidly changing climate, the steward must first know the nature of current relationships between climate and biota, particularly the role and amount of predictable variation (seasonal changes) in moisture and temperature and of unpredictable variation (frequency of extreme weather events). In particular, the sensitivities of the biota to climate and climate change must be characterised. Only certain life stages of each species, only specific organisms within different communities, and only particular communities among those composing the landscapes which comprise our parks and nature reserves will be vulnerable to changes in seasonal and extreme properties of local climate. The land steward must also learn what climate changes are predicted and focus on those to which park biota are particularly vulnerable. In the absence of reliable predictions, a set of "scenarios" derived from logical assumptions can be used to estimate the future course of climate.

Distribution of Climate Variables

The climate variables most easily measured (temperature and precipitation) are not necessarily those which directly affect growth and reproduction of plants. Leaf temperatures (determined by air temperature, solar insolation, humidity, wind speed and turbulence properties, leaf color and anatomy, etc.) are much more important than the air temperatures we measure. Available soil moisture during the growing season (determined by precipitation frequency and intensity, soil structure, air temperature, wind properties, vegetation cover and structure, etc.) is more relevant than daily or monthly total precipitation. However, in most cases the temperature and precipitation data which are commonly available must be used as proxy for the variables actually of concern.

We all recognise the overall temperature structure of the earth in which seasonal and annual temperatures decrease from the equator to the poles. Measurements of leaf temperatures throughout the growing seasons would reveal the same pattern. Fewer people realise that in the presence of abundant moisture, there are very few places on earth in which air temperatures are too warm for growth and reproduction. Photosynthesis reaches optimum rates in many tropical plants above 35 or 40°C, while optimum temperatures for respiration are even higher. Hence, it is difficult to conceive of known temperatures which are too warm for plant growth. This is reflected in the fact that the greatest mass and variety of plants per unit area is found in equatorial rain forests, declining with temperature reductions toward the poles.

In contrast, low temperature very much limits growth as both photosynthesis and respiration are absent in most plants at leaf temperatures below 5°C, with photosynthesis rising only gradually with temperature to reach an optimum between 20 and 40°C, depending on the species. Many tropical plants are killed at temperatures below freezing, and most temperate-zone trees cannot survive temperatures under -40°C. Hence, the direct effects of global warming *per se* may be of greatest importance in the highest latitudes and of least importance toward the equator.

Global precipitation patterns are not as clear as are temperature patterns. A general region of above average rainfall frequency and intensity exists in the vicinity of the equatorial rain forests where moisture-laden air rises into the upper atmosphere. Rising air cools, decreasing its moisture capacity and forcing it to shed this moisture as rainfall. In contrast areas of low rainfall, deserts, are centered on about 30° latitude in both hemispheres where the now dry upper air from the equatorial convective zones subsides. As it sinks, the air warms, increasing its moisture capacity but without a source of moisture. Hence, the atmosphere becomes even dryer, absorbing moisture rather than shedding it as rain. These geographic patterns are often obscured by the effects of topography. For example, rainfall is enhanced in places where moist air moves up the slopes of mountains and is reduced in the lee of the same mountains where the now dry air sinks. This phenomenon is evident at global scales as the "rain shadows" which occur in the lee of great mountain chains such as the Andes of South America, the Pacific Coast Ranges and the Rockies of North America, and the Urals of Russia, which lie across the path of prevailing winds. The same phenomenon occurs at more local scales and this is one of several reasons why precipitation, unlike temperature, is quite variable locally.

Despite the complexities involved in characterising geographic precipitation patterns, one can appreciate that precipitation is increasingly critical to plant growth as one travels from the polar regions to the equator. At the highest latitudes, there is so little warmth that evaporation and water availability do not limit plant growth. Hence, even the polar deserts with weak precipitation may have adequate soil moisture for growth. In contrast, soil moisture becomes the overriding variable defining plant growth and reproductive success with the increasing temperatures and length of growing seasons found toward the equator. Mid-latitude temperate-zone vegetation always has high enough temperatures during the growing season but, frequently, not enough moisture. Equatorial vegetation is subject to temperatures warm enough for growth at any time of the year, making moisture even more important. In Venezuela where dense and diverse rain forests are as rich as any on earth moisture, is plentiful, but just offshore where rainfall is poor, the island of Aruba supports only a sparse desert vegetation.

The following analysis considers the nature of predicted climate changes of greatest relevance, the biotic responses of general concern, and the resultant biotic issues of importance to stewards of the land: international land conservation organisations, national land management agencies and institutions, and local land managers. The analysis is subdivided by thermal zones. A high latitude region which includes the circumpolar boreal forest and treeless tundra is found above about 55° or 60° latitude. The mid-latitudes between about 30° and 60° include temperate forests, the global grain belts of the steppes and the cold deserts. The low latitudes between the equator and about 30° of latitude contain the subtropical and tropical forests, tropical savannahs and grasslands, and hot deserts. Within each of these climatic belts, the analysis is ordered along the moisture gradients between the drought of deserts and the standing water of swamps and marshes.

One concern common to all regions is the potential direct effects of increased atmospheric CO_2 concentrations. These could include increases in photosynthesis and in water use efficiency (i.e., increased carbon fixed in photosynthesis from a constant amount of water) and greater net primary production by individual plants. Although these effects would seem to neutralise some of the negative effects of climate change by enhancing the vigor of all species, species growing in mixed stands cannot all grow better. Rather, some will gain competitive advantages over others, reducing their growth. Those plants most sensitive to and likely to profit from effects of increased CO_2 use the C_4 photosynthetic pathway (trees and shrubs, temperate zone grasses). Tropical grasses and other herbaceous species do not share increased growth effects from greater CO_2 concentrations.

Körner (1993) has proposed classes of plants which are likely to gain a relative growth advantage under enhanced CO_2. For example, annuals are likely to undergo greater growth increments than deciduous perennials and trees, which in turn would do better than evergreen perennials and trees. Young trees would grow best, compared with established trees which would do better than old trees. Competitive advantage would be conferred upon species which are early successional (versus late successional), large fruited (versus small fruited), and nitrogen fixing and mycorrhizal (versus non-nitrogen fixing and non-mycorrhizal). Ecosystems of greater sensitivity to enhanced atmospheric CO_2 concentrations include non-forested (versus forested) steppes, and communities of high altitude (versus low altitude), terrestrial (versus aquatic), saline (versus fresh water), and those of warm (versus cold) climates (Körner, 1993). Actual competitive interactions have not been observed but the reader can draw some conclusions regarding the species which are likely to become dominant and those which may become more vulnerable to competition by others as a result of enhanced atmospheric CO_2 concentrations.

Cold Regions

a. Projected Climate Changes

The climate changes of most concern in high latitude regions are increases in temperature. Initial attempts to document trends will be hampered by the great annual variability in weather in the high latitudes, by the weak regional correlation of precipitation trends and by the scarcity of long weather records. However, certain key properties of the environmental changes can be defined. Temperature increases from increasing greenhouse gases are predicted to be greatest at highest latitudes. An estimate from two different models in 1987 (Jäger, 1988) suggested that 3°C was a "moderate" estimate of average warming in the boreal latitudes, during the next century. This includes about 1.5-2.0°C/century in summer and 6-7°C/century in winter. The most recent climate model results are similar (Mitchell *et al.,* 1990).

Both the results from the Jäger compilation and the more recent collections agree that winter precipitation and soil moisture should increase in high latitudes as more precipitation falls, and as more of it falls as rain instead of snow. These changes in climate forcing must eventually become intense and rapid, although for the next few decades, they may become evident as a much wider range of temperature and precipitation extremes than has ever been recorded in cold regions.

The projections involving warming suggest a significantly longer growing season, with proportionately more annual heat units (degree days), considerable retreat of permafrost and a decline in annual cover by high-albedo snow, but with less change in the July mean temperatures. Intensified summer cloudiness and precipitation is a likely outcome in high latitude regions because warming will increase evaporation rates. This could further reduce the weak CO_2-induced summer warming resulting in long, cool maritime-like growing seasons in today's dry continental-interior boreal forests and woodlands. Presently, continental vegetation under July mean temperatures of 10-12°C consists of shrub-tundra but a maritime version of these temperatures produces dense stands of conifers such as those found in Valdez in Alaska and Bergen in Norway.

b. Scientific Issues

There is a general dichotomy in any local area between those communities found on dry interfluvial uplands and those in the intervening wetlands which are formed by cold region soil processes (development of patterned ground, peatlands, other areas of restricted drainage). However, unlike the temperate and tropical discussions below, it is difficult to order discussion of climate effects along precipitation gradients from arid to humid in the high latitudes because little importance can be ascribed to geographic variation in precipitation. Although certain important species are moisture-sensitive (e.g., balsam fir, *Abies balsamea,* in North America), the overall structure of the vegetation (stem numbers and size, canopy height) does not differ significantly with the presence or absence of these species.

The scientific issues of greatest concern in the high latitudes involve the global carbon balance and temperature-mediated soil moisture shifts. Because organic matter decomposes very slowly in cold temperatures, soil carbon content is quite high in the region. The concern is that a small amount of warming in non-permafrost areas may cause a large increase in the decomposition rate, releasing great amounts of CO_2 and methane to the atmosphere and further enhancing the greenhouse effect. Rapid warming may also generate very rapid retreat of permafrost, uncovering an added enhancement of peat and organic matter for decomposition.

The nature of the wetlands of arctic regions could change drastically and over large regions, inducing unknown but negative effects on species which require the *status quo.* For example, nesting areas in tundra wetlands occupied by now-plentiful wildfowl could disappear in the course of a decade or two. Finally, high latitude plant species that are limited primarily by warmth, as well as whole ecosystems, could become extinct as the cold regions to which they are adapted allow them to grow become increasingly scarce.

c. Management Concerns

The great variation in weather and climate from season to season and from year to year is matched by the extremely variable nature of high latitude vegetation. Boreal forests are buffeted by catastrophic disturbances from which recovery may take hundreds or even thousands of years. Fires and insect attacks decimate large and continuous areas which must be recolonised a few kilometers at a time by species which may have a good establishment year only once in several decades. At the high latitude limit of forest growth, fire may be followed by growth of lichen mats that inhibit establishment of tree seedlings and that may persist for hundreds of years.

Parks and reserves in high latitude regions must be very large to accommodate the characteristic large-scale disturbances and to prevent even the most gradual climate changes resulting in catastrophic responses. Possible catastrophic impacts may involve melting of permafrost throughout a region and concomitant loss of patterned-ground wetlands, invasion by insect defoliators which are no longer eliminated by specific winter low temperatures, or shifts in fire frequency from once every several decades to every several years. Because biotic diversity in high latitude communities is very low (few species, each with many individuals), many species can grow in pure stands or can overwhelmingly dominate stands. Hence, the decimation of a single species population becomes a serious loss to the ecosystems in which it is found.

Parks with little vertical relief where there are only few small areas in which slight amelioration of stress can be found are particularly vulnerable. In contrast, mountainous regions contain high landscape and habitat diversity, and stressed populations and communities can occupy nearby habitats (e.g., shaded canyons, north-facing slopes) in which the stresses are at least temporarily reduced to tolerable levels. The high landscape diversity of montane areas also reduces the frequency and intensity of catastrophic disturbances; natural firebreaks are frequent and insect populations cannot become as dense where grazing fragments the habitat

Temperate Regions

a. Projected Climate Changes

Climate changes in temperate regions may be significantly different from those of high latitudes. While warming in both regions is expected to be greater in winter than in summer, temperate regions may be subject to a more even distribution of warming through the year. Jäger (1988) suggests that a moderate scenario of mid-latitude warming would be 2.4-3.0°C/century in summer and 3.6-4.2°C/century in winter. Maximum warming is estimated at 6.4-8.0°C/century in summer and 9.6-11.2°C/century in winter. Significant decreases in soil moisture during the longer growing seasons may become common, particularly in mid-continental regions (Manabe & Wetherald, 1987). Climate models suggest that as precipitation decreases, year-to-year differences also decrease (Mitchell *et al.,* 1990). However, this result is counter to trends observed in the modern landscape where increasing aridity is paralleled by increases in the annual variability in precipitation amount and frequency, with proportionately more years in which precipitation is below normal, and fewer years in which it is much greater than normal. Unfortunately, the midcontinental areas of decreasing precipitation include the already arid steppes which depend upon a consistent supply of soil moisture during the first half of the growing season to produce much of the world's non-rice cereal grains.

Although catastrophic disturbance by insects and large wildfires has been less important in temperate than in cold regions, both warming and drought could enhance these disturbances in temperate zones. Wanning, particularly in winter, may allow insects and fungi to survive at much higher latitudes than they now can, inducing invasions by many subtropical or warm-temperate pathogenic organisms. Drought may enhance the frequency of large wildfires, particularly in large areas of trees defoliated or killed by pathogen attacks. These large-scale disturbances are likely to remain rare because the midlatitudes are occupied by the major developed countries which can afford actions to control fire and insect outbreaks.

Possibly more important to biotic communities than the magnitude of wanning or of precipitation change is the speed of climate change. This is not likely to be as important in high latitude vegetation communities which are tolerant of widespread disturbance and extensive variation in environmental conditions. Mid-latitude species and communities, particularly forest communities, may not be so adaptable since the life cycles of their constituent dominant species may take 50-200 years to complete. The predicted rate of wanning between 3 and 11 °C/century is one or two orders of magnitude greater than any change encountered by vegetation in the past 100,000 years (Solomon & Leemans, 1990). Such a rate of climate change could, for example, result in summer temperatures which exceed those presently found throughout the geographic range of red pine (*Pinus resinosa* Ait.).

b. Scientific Issues

The scientific issues of concern in temperate regions vary according to the presently available soil moisture; effects on soil moisture of shifting patterns of precipitation; and the role of temperature increases in changing soil moisture through increased rates of evaporation. In desert ecosystems the critical variables involve increased rather than decreased seasonal precipitation. Adaptations of desert species and ecosystems make them very well suited to drought which itself is a highly variable property of desert climates. Many of the same adaptations to drought, however, keep plant species (especially perennials) from growing rapidly during times of decreased stress. Hence, non-desert species, from desert grasslands, thorn scrub woodlands, and so on, can easily outcompete the desert species in the presence of adequate moisture and, thereby, pose a serious threat to desert ecosystems.

In Mediterranean shrublands (i.e., arid regions in which moisture falls in the winter season) and steppes, concern is directed more towards species competition and grazing. Any change in the amount of moisture is likely to induce important shifts in species composition, enhancing competitive positions either of woodland or of desert shrub vegetation. With increasing human population, these steppe regions which are traditionally used for animal husbandry may receive much greater grazing pressure. Potential decline in fire frequency, a force which maintains vigor of Mediterranean shrublands and steppe vegetation, is of concern.

Woodlands, savannahs and forests are also controlled in large part by precipitation patterns. At least 50 cm/year of precipitation is required to support growth and regeneration of trees. Slight changes in that quantity can produce great shifts in vegetation structure, leading to open woodlands, savannahs and grasslands with lesser amounts, and to closed-canopy forests with greater amounts. In addition to determining the presence or absence of trees, soil moisture availability directly defines forest density and biomass (Bassett, 1964). Because trees control the light and moisture conditions for plants growing below them, forest structure is a key variable controlling the nature of forest communities.

Among the various tree life stages, seedlings are most vulnerable to shifts in precipitation patterns or amounts. Most seedlings can survive and become established only within very narrow limits of soil moisture and sunlight and slight changes in soil moisture values can completely obliterate a season's seedling crop. Loss of a cohort may not be evident in change to forest structure for decades or even a century as the established trees continue to survive under increasing environmental stress.

Temperate wetlands are also under the control of precipitation, particularly as precipitation determines the level of the water table. Changes in seasonal distribution of precipitation may be just as important as the absolute amount of precipitation. Coastal ecosystems (dune communities, salt-spray forests, saltmarshes, mangroves) depend upon precipitation for fresh water although water tables may be more directly controlled by sea level. In these coastal communities, storminess and its role in determining the magnitude of storm surges becomes a critical variable. In all the temperate zone cases, temperature produces minor or unimportant responses in plant species and communities.

c. Management Concerns

A major concern for park management in all areas is to begin monitoring the appropriate weather variables and biotic populations and communities. One cannot expect to design a mitigation strategy to fit local priorities and needs until directional changes in biotic population and community properties can be identified and related to their specific environmental causes. Yet this is not a trivial task. Like high latitude populations stressed by low temperature, the mid-latitude populations stressed by low moisture availability may be very plastic in their response to environmental variation. Some annual plant species can await the appropriate moisture conditions for years without germinating. Temperate-zone trees are adapted to survive annual differences in weather that may be encountered at a given spot only once in 200 years. Hence biotic variation within populations and communities may be too high to distinguish biotic trends in response to environmental changes. The only remedy for this problem is *a priori* knowledge of the changes expected and their likely effects on populations and communities.

In desert areas, monitoring the onset and effect of greater precipitation (amounts, frequencies) is likely to be of greatest importance. Highly sensitive indicators of biotic response to moisture include the amphibians (hard to monitor but very reliable) and bird populations (easily monitored but less reliable, especially migrants whose populations may be controlled from elsewhere). The ratio of grass species which use the C_3 (Calvin Cycle) photosynthetic pathway versus those which use the C_4 (Hatch and Slack Cycle) pathway should provide a particularly reliable indicator of biotic responses in arid and semiarid grasslands and Mediterranean shrublands.

In forest-grassland border areas (savannahs, open woodlands), the ratio of herbaceous to tree species as well as the cover by each could provide critical evidence of functional changes in biotic communities. Within closed-canopy forests, seedlings are the most vulnerable life stage, and their establishment must be monitored carefully, since established trees may not be effected by climate change for decades.

The wetlands are so closely linked to water tables that the water tables themselves, along with other hydrological properties (e.g., flow rates in streams, storm surges on coasts) are the critical environmental property to monitor. If vegetation begins to respond to water table changes, it is probably too late to mitigate the effects on biota, that is, the woody perennials and trees are probably already dying.

Tropical Regions

a. Projected Climate Changes

The relevant climate changes expected in tropical regions all involve moisture. Temperature increases are expected to be moderate, ranging between 2 and 3°C or less (maximum 5.6 to 7.7°C; Jäger, 1988) in both summer and winter. However, since there is already enough warmth to allow plants to grow year round in tropical areas and in many subtropical regions, temperature increases are unlikely to have much impact Temperature considerations are of significance only where they control the availability of soil moisture through evaporation.

Enhanced precipitation is predicted throughout the tropics (Mitchell *et al.,* 1990). Those areas in which precipitation is plentiful are expected to receive even more rainfall but the arid tropics may not receive enough rainfall to balance the increased evaporation from warming (Jäger, 1988). Although increases in soil moisture are projected in some regions (e.g., monsoonal India and northern Australia, east-central Africa and northern Argentina), many tropical regions (central America, Amazonia, equatorial Africa, the Indochina Peninsula) may not benefit from increased rainfall, as the soil moisture remaining after evaporation and runoff may be reduced significantly in winter or summer or both (Mitchell *et al.,* 1990).

b. Scientific Issues

As in the case of temperate zone vegetation discussed above, the scientific issues of concern in tropical aspects of global change can be summarised in terms of moisture availability. However, natural communities in all moisture classes are expected to undergo enhanced and possibly permanent disturbance from intensification of agricultural land use, accompanied by enhanced soil erosion and degradation and nutrient depletion. The combination of rapid population growth rates and heavy reliance on natural resource utilisation is particularly of concern for natural vegetation. Particularly vulnerable to increasing land use pressures will be protected areas and buffer zones, coastal forests, and fragile watersheds. Those communities are not particularly resilient to disturbance.

In the arid and semi-arid tropics, a critical issue will be climate-induced desertification. Climate change can directly affect these regions through general decreases in precipitation (Mitchell *et al.*, 1990) which would produce lower average annual moisture availability. However, additional pressure may come from enhanced frequency of ENSO (El Nino Southern Oscillation) events which reduce moisture in semi-tropical regions for two to three years at a time every four to seven years. Initially, the most vulnerable ecosystems and habitats will be oases and patchy or unique habitats. Their rarity attests to the narrow environmental limits within which they exist: their resilience to change is very low.

Wildfire timing and frequency is also expected to change in semi-arid tropics, increasing drastically in those areas subjected to increased multiannual droughts. Although arid lands rarely contain dense enough vegetation to fuel intense fires, dry thorn scrub and woodlands could be very vulnerable to increasing frequency of small and large-scale wildfires.

In the more moist tropical landscapes dominated by grasslands and savannahs, there is still considerable interest in desertification. Concern centers on loss of the grasslands that support large herds of domesticated and wild grazers, and potential local and regional extinctions of the latter. Particularly vulnerable are fragile watersheds, protected areas and buffer zones. Enhancement of wildfire frequency is also of interest but because fire is required for maintenance of community structure, increased frequency is not considered important.

Seasonally-dry deciduous forests also could undergo increased fire frequency with increases in drought. Here, results could be disastrous with potential catastrophic losses of live trees and permanent replacement by thorn scrub or savannah vegetation over a very short period of time. Hydrological changes such as shifts in atmospheric circulation could threaten cloud forests which depend upon gaseous atmospheric moisture. However, so little detail has been predicted concerning this aspect of potential climate change that monitoring or mitigation seems premature.

Wet tropical forests will be threatened by desiccation from increasing length and frequency of droughts. The precipitation changes previously described may be very seasonal, producing a distinct dry season in which growth ceases in current rain forests. Significantly, drought acts directly on individuals; those without morphological or physiological adaptations to drought will be killed. In contrast, an overabundance of moisture (in the absence of flooding) usually acts through changed competitive capability; drought-adapted species can grow better with good moisture, but they will simply be outcompeted by species which do not labor under the same drought-adaptation apparatus. Species from moist tropical forests are the least drought-adapted species in the tropics and hence are directly vulnerable to decreases in soil moisture, rather than to enhanced growth of competitors. As a result, significant decreases in biodiversity among species which "have nowhere else to go" may become a more serious problem in the wet tropics than elsewhere.

Certain physiological growth temperature thresholds are also of concern in wet tropical forests, in particular, chill-dependent flowering in mid-elevation species. Such phenological events as flowering and fruiting are often initiated by low temperatures. In addition, the high montane communities may be driven off mountain ranges as the climate to which they are adapted is no longer found even at maximum elevations. The resilience to warming of plants which depend on these threshold temperatures is very low and hence, of serious concern.

It is obvious that many tropical regions are more endangered by current land use practices than by gradual climate change. The deforestation of equatorial tropics continues to accelerate at alarming rates, and climate change impacts may not be measurable within the great variability caused by land use. Yet, effects of the two forces could be intimately intertwined. Land use change may enhance effects of climate change which in turn could generate a permanence to the otherwise temporary disruption of tropical ecosystems by human activities. Recent research (Lean & Warrilow, 1989; Nobre *et al.,* 1990) indicates that deforestation in the Amazon Basin could reduce precipitation there by as much as 20%. Because the projected effects on climate of land use are very seasonal, the nonseasonal tropical rainforest may be unable to reproduce itself following deforestation. Rather, rainforest may regenerate as semi-arid seasonal tropical forest or woodland.

c. Management Concerns

Management of tropical parks and reserves under chronic climate change, like that in temperate regions, will require carefully planned climatic and biotic monitoring strategies. In arid and semi-arid regions, desertification is a critical issue and the indicators of its onset must be documented as early as possible. The likelihood of lower annual precipitation and of greater multi-year drought frequency suggests that detection of precipitation shifts should also be of high priority. In grasslands and savannahs, desertification is also a critical issue, with concern greatest in the case of the potential local and regional extinction of large grazing animals. Monitoring the health and mortality of the grazing herds should be undertaken where programmes are not already in place.

In the seasonally-dry forests, increased wildfire intensity and frequency resulting from increased droughts and enhanced dry matter availability will necessitate serious consideration be given to additional fire management strategies and activities. The concern in wet tropical forests that drought will induce extinctions of non-drought adapted plant species, with concomitant loss of biodiversity implies that areas of unknown species composition be explored and their biota catalogued as soon as possible. Regions with documented floras and faunas should be monitored for losses of the most moisture-dependent species. Reliable rainfall and temperature records will be critical to determine the cause of diversity decline in these wet tropical forest communities as well as for defining risks to which montane species and communities are subject because of absence of low temperature cues for flowering.

Summary

The nature of climate change resulting from greenhouse gas increases will vary locally and regionally much more in the terrestrial biosphere than in the marine biosphere. In addition, specific ways by which climate affects terrestrial biotic communities and populations also will vary strongly with geography. As a result, the regional nature of current climate and biota, of future climate, and of future biotic responses to climate change all must be documented if climate change effects are to be accurately integrated into park management and planning. This synthesis paper is based on formal discussion among participants in the symposium "Impacts of Climate Change on Ecosystems and Species" held at Amersfoort, the Netherlands, 5-6 December, 1991. The paper reviews the continental-scale distributions of present and future climate as the basis for defining changes in key regional processes and the implications of the changes for parkstewards (planners, managers) in each of the regions. It separates the cold boreal, moderate temperate, and warm tropical climates and within each, examines biotic responses to climate along growing-season moisture gradients from annually and seasonally dry to permanently wet environments.

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Protected areas and global climate change: assessing the regional or local vulnerability of vertebrate species

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Abstract

Protected areas are critical for long term monitoring and for implementing regional schemes to reduce extinction rates associated with environmental changes such as those resulting from global warming. The impact of climatic warming on at least some species and habitats within protected areas may be mitigated by appropriate management. Assessing the vulnerability of species to such warming is a first but essential step towards rational allocation of scarce management resources. This must address our ignorance of species' environmental needs in order to establish which species require study most urgently.

We present an approach for analysing vulnerability to climatic warming of terrestrial and aquatic vertebrates in maritime Atlantic Canada. For this region, most global circulation models predict decreased summer precipitation, increased winter rainfall and higher winter temperatures. We developed a system for scoring the sensitivity of species to the predicted consequences of lower summer soil moisture; reduced snow and ice cover; increased minimum winter temperatures; increased winter stream flow; and higher summer and winter water temperatures. While our system estimates vulnerability to specific climatic changes, it does not assess general biological vulnerability. To address the latter, we adapted the scheme of Millsap *et al.* (1990) which also assesses knowledge and management scores for species. To illustrate our approach we discuss a salamander, a turtle, a mammal and two birds in some detail. The combination of assessment systems provides a useful method for ranking overall vulnerability. The approach is readily adaptable to other climates, other species and other kinds of environmental change.

1. Introduction

Significant global warming appears to be inevitable over the next three to five decades, and the only real uncertainties concern how rapidly it will occur and how far it will progress. In general, global circulation models predict that wanning will be greatest at mid to high latitudes in the

Northern Hemisphere, but there is probably no region of the Earth's surface that will be totally unaffected (Abrahamson, 1989; Schneider, 1990). The effects will include alterations to precipitation regimes as well as increases in average annual temperatures even in the semi-arid and humid tropics (Jaeger, 1989). Seasonal redistribution of rainfall may have far more impact on biota than temperature increases alone.

Climate change is not new, and has been a major factor in the evolution of the biota present on the Earth today. What *is* new is the speed of the change. The far slower and less extreme climatic changes that occurred since the most recent glaciation have left Nova Scotia (Figure 1) with a high proportion of disjunct species, especially among vertebrates (Hall & Kelson, 1981; Conant, 1975; Gilhen, 1974; 1984). The unique geography of the province makes it an ecological island, and the unprecedented speed of the changes will result in the predicted warming being essentially an extinction event. There is little chance in the short term (30-50 years) of replacement of terrestrial or aquatic vertebrate species via the only overland corridor. In the case of invertebrates or plants with low vagility, the likelihood is even less. Although Nova Scotia's unique geography has been a major factor giving rise to the high proportion of disjuncts, rapid climate change in *any* geographic setting will tend to fragment and isolate species, making them more vulnerable to extinction. Because protected areas are limited in size

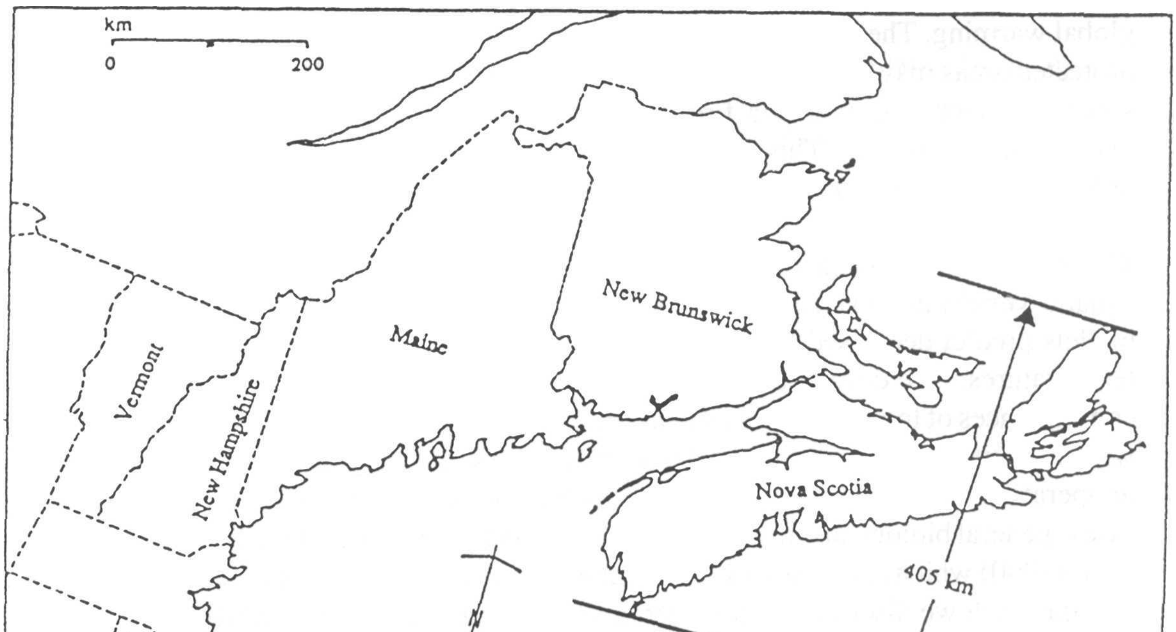

Figure 1.
Nova Scotia. Spanning a north-south distance of only 405 km, and connected to the mainland by a narrow isthmus. because of its orientation, even slight north/south movement of isotherms can have a significant biogeographic impact by isolating or **eliminating** populations at either end. Warming on the scale predicted would thus have a disproportionately greater impact in Nova Scotia than in most continental mid-latitudes.

and often bordered or completely surrounded by disturbed habitats, they are already subject to high stochastic extinction rates. The added impact of climatic change can only speed up the rate of such extinctions.

In 1989 we began to develop a system to evaluate the vulnerability to climatic warming of local terrestrial and aquatic vertebrates. In the initial presentation of our method (Herman & Scott, 1992) we excluded birds in order to reduce the number of species considered and because birds have a greater ability than other vertebrates to escape unfavourable conditions and to invade newly habitable areas. We have since amended and refined our system and present it here in greater detail, with less emphasis on results and more on methodology and approach. We discuss in some depth five species of Nova Scotian vertebrates of varying sensitivity to climate in order to illustrate how the system works, and to demonstrate the value of scoring separately such factors as ignorance of a species' biology as a component of its vulnerability. Ourprincipal goal is to provide a framework and procedures that will enable others to adapt our approach to their own unique habitats, species and future climatic scenarios, and to determine which taxa should be given priority for study or management.

2. Methods

In 1989 we began to develop a system for estimating the vulnerability of vertebrates to global warming. Initially we considered changes to every conceivable factor resulting from climate change that might have an impact on vertebrates, and scored the vulnerability of each species to all of them. Any environmental variable that scored zeros (no effect) for all species within a matrix was eliminated. Since we were concerned with *relative* vulnerability (no system of this sort can deal with absolute vulnerability), we assessed costs only, not benefits. This simplified the analysis and made it easier to identify cases of double or multiple scoring, which was a problem in the early development of the method. We learned that it was important to rigorously separate the *direct* and *indirect* effects of each environmental variable. For example, climate models predict decreased summer precipitation in our region which will affect soil moisture, water table levels and summer stream-flow rates, insolation, cloud-cover, and surface soil and water temperatures. We had to distinguish between the *direct* and *indirect* effects of reduced summer rainfall. If the effect was direct, then it mattered if individuals of a species, or the substrate they were on, were *actually wetted by rain.* This would be of concern for the red eft, the terrestrial stage of an aquatic salamander, which only feeds when it is raining, and for the spring migration to spawning sites and general dispersal movements of amphibians which are *directly* triggered by rainfall and the wetting of the substrate over which they have to travel (Duellman & Trueb, 1986). An *indirect* effect would be the increased hours of sunshine resulting from reduced cloud cover which would tend to raise soil temperatures and in turn could skew the sex ratios of hatchling turtles in nests on exposed lakeshore beaches or other open sites. A species that scored for higher summer soil temperatures should not also be scored for the *direct* effect of reduced rainfall, unless it is known that it is directly affected by being rained upon.

Table 1 presents the environmental variables that had at least one non-zero score. These are appropriate for Nova Scotian species, habitats and environmental conditions; variables relevant to other climates, habitats and species may differ greatly from these, although the process of selecting them should be similar.

Table 1.
Variables used in scoring climatic sensitivity in Nova Scotian aquatic and terrestrial vertebrates. Scoring for all variables (except **1** and **7 f**) is the same: greatly reduced/ increased or very costly = 2; moderately reduced/increased or moderately costly = 1; unreduced/unincreased or no cost = 0.

1. **Life history environments:** the number of different environments (i.e. terrestrial, aquatic) occupied during development, or seasonally during adulthood (amphibians and reptiles only). The more environments occupied, the greater the likelihood that a species will be affected.
2. **Reduced summer soil moisture** and its *direct* impact on:
   a) **food supply or access to food supply** (including foraging ability)
   b) **dispersal ability**
   c) **habitat reduction or loss of quality**
   d) **exposure to predation**
   e) **physiological stress** (including water, oxygen and thermal stress)

3. **Lower summer water table** and its *direct* impact on:
   a) **food supply or access to food supply** (including foraging ability)
   b) **dispersal ability**
   c) **habitat reduction or loss of quality**
   d) **exposure to predation**
   e) **physiological stress** (including water, oxygen and thermal stress)

4. **Reduced summer rainfall** (amphibians and reptiles only) (the physical or other *direct* effects of the rainfall itself, separate from 2 and 3) and their impact on:
   a) **food supply or access to food supply** (including foraging ability)
   b) **dispersal ability**

5. **Lower summer streamflow rates** and their *direct* impact on:
   a) **food supply or access to food supply** (including foraging ability)
   b) **dispersal ability**
   c) **habitat reduction or loss of quality**
   d) **exposure to predation**
   e) **physiological stress** (including water, oxygen and thermal stress)

6. **Increased summer water-surface temperature** (amphibians and reptiles only) and its *direct* impact on:
   e) **physiological stress** (including water, oxygen and thermal stress)

7. **Increased summer soil temperature** (the result of increased insolation because of reduced summer rainfall) and its *direct* impact on:
   e) **physiological stress** (including water, oxygen and thermal stress)
   f) **skewing of hatchling sex ratio** (turtles only)
   likely to be skewed = 2
   not likely to be skewed = 0

8. **Increased winter water-bottom temperature** (amphibians and reptiles only) and its *direct* impact on:
   e) **physiological stress** (including water, oxygen and thermal stress)

9. **Reduced snow and ice cover** and its *direct* impact on:
   a) **food supply or access to food supply** (including foraging ability)
   b) **dispersal ability**
   c) **habitat reduction or loss of quality**
   d) **exposure to predation**
   e) **physiological stress** (including water, oxygen and thermal stress)

10. **Increased winter/spring flooding** and its *direct* impact on:
   a) **food supply or access to food supply** (including foraging ability)
   b) **dispersal ability**
   c) **habitat reduction or loss of quality**
   d) **exposure to predation**
   e) **physiological stress** (including water, oxygen and thermal stress)

Millsap *et al.* (1990) introduced an assessment and scoring scheme for measuring vulnerability in Florida vertebrates, to land use changes associated with increasing human population and development. This system comprised three basic categories of variables: a) *biological,* including estimated population size and trend, range size, distribution trend, reproductive potential and ecological specialisation; b) *action,* including knowledge of distribution, population trends and limiting factors, as well as current management activity; and c) *supplemental,* including taxonomic uniqueness and harvest variables. Taxonomic uniqueness does not contribute to vulnerability, but it *is* a rough measure of the genetic value of a species and should be part of any assessment. Because this is a ranking system, in order to assign priorities it is important to know not only which species are most at risk, but which most urgently need study. Although it is debatable whether an 'ignorance score' is directly relevant to gauging vulnerability, it is certainly relevant in terms of our responses to perceived threats. Inaction through ignorance can have as great an impact on a species as environmental change itself. We adapted or modified some of these variables to suit Nova Scotia conditions and the smaller diversity of vertebrate groups (Appendix 1). The value of combining Millsap *et al*'s (1990) approach to scoring general vulnerability with our own approach, which focuses specifically on climatic sensitivity, is evident. We produced species/variable matrices for Nova Scotia's terrestrial and aquatic mammals, amphibians and reptiles by combining these two scoring systems. Matrix values are assigned on the basis of a mix of data derived from a literature review covering both field and experimental studies; analysis of range shape and size, particularly latitudinal extent, which is an indicator of climatic tolerance, and fragmentation; personal observations and data;expert opinion from authorities on particular taxa; and, where data were totally lacking, from educated guesses based on what is known of the biology of the taxonomic group concerned.

3. Results and Discussion

3.1 The matrix assessment approach

We present sample matrices of general vulnerability (Table 2) and climatic sensitivity scores for Nova Scotian salamanders (Table 3), turtles (Table 4) and shrews (Table 5). General vulnerabilities of these three groups are relatively high in comparison to other amphibian, reptile and mammal groups (Herman & Scott, 1992). In most cases climatic sensitivity scores contribute little to the general vulnerability scores - usually much less than do the action scores.

The climatic sensitivity matrices are dominated by zero values, and for some parameters contain only zeros; in these cases species in other groups of Nova Scotian amphibians, reptiles and mammals scored positively (Herman & Scott, 1992). The prevalence of zeros reflects in part our conservative approach but also the likelihood that most species are insensitive to most parameters.

Such matrices lend themselves to analysis of score distributions within taxonomic or ecological groups. This type of analysis is useful for recognising patterns that could affect management decisions. For example, analysis of winter and summer factors in the sensitivity scores of shrews shows that they are far more sensitive to changes in conditions during winter than during summer (Figure 2).

Table 2.

General vulnerability scores for Nova Scotian salamanders, turtles and shrews.

Salamanders: Al =*Ambystoma laterale*; **Am** = *Ambystoma maculatum*; **Nv** = *Notophthalmus viridescens*; **Pc** = *Plethodoncinereus*; **Hs** = *Hemidactylium scutatum.* **Turtles**:Cs = *Chelydra serpentina*; **Ci** = *Clemmys insculpta*; **Eb** = *Emydoidea blandingi*; **Cp** = *Chrysemys picta.* **Shrews: Sa** = *Sorex arcticus*; **Sc** = *Sorex cinereus*; **Sf** = *Sorex fumeus*; **Sg** = *Sorex gaspensis*; **Sd** = *Sorex dispar*; **Sp** = *Sorex palustris;* **Sh** = *Sorex hoyi*; **Bb** = *Blarina brevicauda.* Note: Reproductive Potential Scores were generated before we added the parameter "Average number of reproductive years per female". In short-lived species, this parameter would increase the score significantly.

	SALAMANDERS					**TURTLES**				**SHREWS**							
	Al	**Am**	**Nv**	**Pc**	**Hs**	**Cs**	**Ci**	**Eb**	**Cp**	**Sa**	**Sc**	**Sf**	**Sg**	**Sd**	**Sp**	**Sh**	**Bb**
BIOLOGICAL VARIABLES																	
life-history environments	2	2	3	2	2	2	1	2	2								
population size	0	0	0	0	3	0	7	10	3	3	0	0	7	10	0	3	0
population trend	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
range size	3	0	0	0	3	3	3	10	3	7	0	0	7	10	0	3	0
distribution trend	2	2	2	2	2	2	2	2	2	2	0	2	0	0	2	2	2
population concentration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
reproductive potential	1	1	3	2	2	6	8	8	6	2	2	2	2	2	1	1	1
reproductive specialization	0	0	2	0	4	0	0	0	0								
dietary specialization	0	0	4	4	0	0	0	0	0	0	0	0	2	2	2	0	0
habitat specialization	2	0	0	0	2	0	0	2	0	4	0	0	4	4	2	0	2
climatic sensitivity	9	7	13	11	7	2	22	16	6	21	8	14	5	5	7	8	13
BIOLOGICAL SCORE	**23**	**16**	**31**	**25**	**29**	**19**	**47**	**54**	**26**	**43**	**14**	**22**	**31**	**37**	**18**	**21**	**22**
ACTION VARIABLES																	
distribution knowledge	0	5	5	5	10	5	5	0	5	5	0	5	5	5	5	10	5
population trend knowledge	5	5	5	5	8	5	5	5	5	10	5	7	10	10	5	10	5
limiting factor knowledge	5	5	5	5	10	5	5	5	5	5	5	5	10	10	5	5	5
management activities	10	10	10	10	10	10	10	0	10	10	10	10	5	10	10	10	10
ACTION SCORE	**20**	**25**	**25**	**25**	**38**	**25**	**25**	**10**	**25**	**30**	**20**	**27**	**30**	**35**	**25**	**35**	**25**
SUPPLEMENTAL VARIABLES																	
systematic significance	3	0	0	0	6	4	2	6	0	1	0	0	3	1	0	0	0
% of total range in NS	1	1	1	1	2	1	2	1	1	1	1	2	5	2	1	1	1
harvest in NS	0	0	0	0	0	3	3	1	3	0	0	0	0	0	0	0	0
SUPPLEMENTAL SCORE	**4**	**1**	**1**	**1**	**8**	**8**	**7**	**8**	**4**	**2**	**1**	**2**	**8**	**3**	**1**	**1**	**1**
TOTAL SCORE	**47**	**42**	**57**	**51**	**75**	**52**	**79**	**72**	**55**	**75**	**35**	**51**	**69**	**75**	**44**	**57**	**48**

EGGS/LARVAE	Al	Am	Nv	Pc	Hs
reduced summer soil moisture (totals)	**0**	**0**	**2**	**4**	**1**
a) food supply/access to food	0	0	1	1	0
b) dispersal mobility	0	0	0	1	0
c) habitat reduction/loss of quality	0	0	1	1	1
d) exposure to predation	0	0	0	0	0
e) physiological stress	0	0	0	1	0
lower summer water table (totals)	**2**	**2**	**2**	**0**	**1**
a) food supply/access to food	0	0	0	0	0
c) habitat reduction/loss of quality	1	1	1	0	1
d) exposure to predation	1	1	1	0	0
e) physiological stress	0	0	0	0	0
lower summer precipitation (totals)	**0**	**0**	**4**	**1**	**0**
a) food supply/access to food	0	0	2	0	0
b) dispersal mobility	0	0	2	1	0
highersummer soll temperatures(totals)	**0**	**0**	**0**	**0**	**0**
e) physiological stress	0	0	0	0	0
f) hatchling sex ratios	0	0	0	0	0
winter water-bottom temp up (totals)	**0**	**0**	**0**	**0**	**0**
e) physiological stress	0	0	0	0	0
summer water-surface temp up (totals)	**1**	**0**	**0**	**0**	**0**
e) physiological stress	1	0	0	0	0
lower summer stream-flow rates (totals)	**0**	**0**	**0**	**0**	**0**
a) food supply/access to food	0	0	0	0	0
b) dispersal mobility	0	0	0	0	0
c) habitat reduction/loss of quality	0	0	0	0	0
d) exposure to predation	0	0	0	0	0
e) physiological stress	0	0	0	0	0
SCORE	**3**	**2**	**8**	**5**	**2**

ADULTS	Al	Am	Nv	Pc	Hs
life-history environments	**2**	**2**	**3**	**2**	**2**
reduced summmer soil moisture (totals)	**2**	**1**	**0**	**3**	**0**
a) food supply/access to food	1	1	0	1	0
b) dispcrsal mobility	0	0	0	0	0
c) habitat reduction/loss of quality	1	0	0	1	0
d) exposure to predation	0	0	0	0	0
c) physiological stress	0	0	0	1	0
lower summer water table (totals)	**0**	**0**	**2**	**0**	**2**
a) food supply/access to food	0	0	0	0	0
b) dispersal mobility	0	0	0	0	0
c) habitat reduction/loss of quality	0	0	1	0	2
d) exposure to predation	0	0	1	0	0
e) physiological stress	0	0	0	0	0
reduced summer rainfall (totals)	**2**	**2**	**0**	**1**	**1**
a) food supply/access to food	0	0	0	0	0
b) dispersal mobility	2	2	0	1	1
winter water-botttom temp up (totals)	**0**	**0**	**0**	**0**	**0**
e) physiological stress	0	0	0	0	0
higher winter max air temp (totals)	**0**	**0**	**0**	**0**	**0**
d) exposure to predation	0	0	0	0	0
e) physiological stress	0	0	0	0	0
lower summer stream-flow rates (totals)	**0**	**0**	**0**	**0**	**0**
a) food supply/access to food	0	0	0	0	0
b) dispersal mobility	0	0	0	0	0
c) habitat reduction/loss of quality	0	0	0	0	0
d) exposure to predation	0	0	0	0	0
e) physiological stress	0	0	0	0	0
SCORE	**6**	**5**	**5**	**6**	**5**
TOTAL	**9**	**7**	**13**	**11**	**7**

Table 3.

Climatic sensitivity scores for Nova Scotian salamanders.

Al = *Ambystoma laterale*; **Am** = *Ambystoma maculatum*; **Nv** = *Notophthalmus viridescens*; **Pc** = *Plethodon cinereus*; **Hs** = *Hemidactylium scutatum.*

EGGS/LARVAE	Cs	Ci	Eb	Cp
reduced summer soil moisture (totals)	**0**	**5**	**2**	**2**
a) food supply/access to food	0	1	0	0
b) dispersal mobility	0	1	0	0
c) habitat reduction/loss of quality	0	1	0	0
d) exposure to predation	0	0	0	0
e) physiological stress	0	2	2	2
lower summer water table (totals)	**0**	**1**	**1**	**1**
a) food supply/access to food	0	1	0	0
c) habitat reduction/loss of quality	0	0	1	1
d) exposure to predation	0	0	0	0
e) physiological stress	0	0	0	0
lower summer precipitation (totals)	**0**	**0**	**0**	**0**
a) food supply/access to food	0	0	0	0
b) dispersal mobility	0	0	0	0
higher summer soil temperatures (totals)	**2**	**3**	**3**	**2**
e) physiological stress	0	1	1	0
f) hatchling sex ratios	2	2	2	2
winter water-bottom temp up (totals)	**0**	**1**	**1**	**0**
e) physiological stress	0	1	1	0
summer water-surface temp up (totals)	0	0	1	0
c) physiological stress	0	0	1	0
lower summer stream-flow rates (totals)	**0**	**7**	**4**	**0**
a) food supply/access to food	0	1	1	0
b) dispersal mobility	0	1	1	0
c) habitat reduction/loss of quality	0	2	1	0
d) exposure to predation	0	2	1	0
e) physiological stress	0	1	0	0
SCORE	**0**	**14**	**9**	**3**

ADULTS	Cs	Ci	Eb	Cp
life-history environments	**2**	**2**	**2**	**2**
reduced summmer soil moisture (totals)	**0**	**2**	**0**	**0**
a) food supply/access to food	0	2	0	0
b) dispersal mobility	0	0	0	0
c) habitat reduction/loss of quality	0	0	0	0
d) exposure to predation	0	0	0	0
e) physiological stress	0	0	0	0
lower summer water table (totals)	**0**	**2**	**0**	**0**
a) food supply/access to food	0	0	0	1
b) dispersal mobility	0	0	0	0
c) habitat reduction/loss of quality	0	2	0	1
d) exposure to predation	0	0	0	1
e) physiological stress	0	0	0	0
reduced summer rainfall (totals)	**0**	**0**	**0**	**0**
a) food supply/access to food	0	0	0	0
b) dispersal mobility	0	0	0	0
winter water-botttom temp up (totals)	**0**	**1**	**1**	**0**
e) physiological stress	0	1	1	0
higher winter max air temp (totals)	**0**	**0**	**0**	**1**
d) exposure to predation	0	0	0	0
e) physiological stress	0	0	0	1
lower summer stream-flow rates (totals)	**0**	**1**	**4**	**0**
a) food supply/access to food	0	0	1	0
b) dispersal mobility	0	0	1	0
c) habitat reduction/loss of quality	0	1	2	0
d) exposure to predation	0	0	0	0
e) physiological stress	0	0	0	0
SCORE	**2**	**8**	**7**	**3**
TOTAL	**2**	**22**	**16**	**6**

Table 4.
Climatic sensitivity scores for Nova Scotian turtles.
Cs = *Chelydra serpentina*; Ci = *Clemmys insculpta*; Eb = *Emydoidea blandingi*; Cp = *Chrysemys picta.*

Table 5.
Climatic sensitivity scores for Nova Scotian shrews. Sa = *Sorex arcticus*; Sc = *Sorex cinereus*; Sf = *Sorex fumeus*; Sg = *Sorex gaspensis*; Sd = *Sorex dispar*; Sp = *Sorex palustris*; Sh = *Sorex hoyi*; Bb = *Blarina brevicauda.*

	Sa	**Sc**	**Sf**	**Sg**	**Sd**	**Sp**	**Sh**	**Bb**
lower summer soil moisture (totals)	**3**	**1**	**3**	**1**	**1**	**2**	**1**	**2**
a) food supply/access to food	1	1	2	1	1	1	1	1
b) dispersal ability	0	0	0	0	0	0	0	0
c) habitat reduction/loss of quality	2	0	1	0	0	1	0	1
d) exposure to predation	0	0	0	0	0	0	0	0
lower summer water table (totals)	**3**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
a) food supply/access to food	1	0	0	0	0	0	0	0
b) dispersal ability	2	0	0	0	0	0	0	0
c) habitat reduction/loss of quality	0	0	0	0	0	0	0	0
d) exposure to predation	0	0	0	0	0	0	0	0
reduced snow/ice cover (totals)	**5**	**6**	**6**	**4**	**4**	**5**	**6**	**6**
a) food supply/access to food	2	1	1	1	1	1	1	1
b) dispersal ability	0	1	1	1	1	1	1	1
c) habitat reduction/loss of quality	0	1	1	0	0	0	1	1
d) exposure to predation	1	1	1	0	0	1	1	1
e) physiological stress	2	2	2	2	2	2	2	2
more winter/spring flooding (totals)	**10**	**1**	**5**	**0**	**0**	**0**	**1**	**5**
a) food supply/access to food	2	0	1	0	0	0	0	1
b) dispersal ability	2	0	1	0	0	0	0	1
c) habitat reduction/loss of quality	2	0	1	0	0	0	0	1
d) exposure to predation	2	0	1	0	0	0	0	1
e) physiological stress	2	1	1	0	0	0	1	1
Climatic Sensitivity Score	**21**	**8**	**14**	**5**	**5**	**7**	**8**	**13**

An analysis of action scores for Nova Scotian amphibians and reptiles (Figure 3) reveals our monumental ignorance of their likely responses to climate changes. This pattern will probably be the rule rather than the exception for most faunal groups.

3.2 Species accounts

The four-toed salamander *Hemidactyliwn scutatum* is Nova Scotia's rarest salamander, known from only 14 localities in the province. It is restricted to sphagnum areas bogs during breeding season (Gilhen, 1984), but can be found in adjacent woodlands outside the breeding season. Populations are highly disjunct and appear to be small wherever they occur. The action score for this species accounts for half of the general vulnerability score, and is by far the highest for any salamander reflecting the specie's low density populations and cryptic habits which result in inadequate data on its distribution, population status and general biology. The low sensitivity score reflects our belief that sphagnum bog habitats, which tend to be deep, will be relatively unaffected by the predicted lower summer water tables. The species' non-breeding habitat may

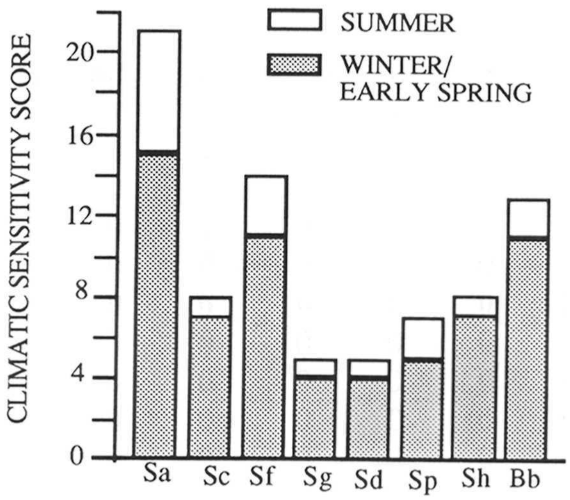

FIGURE 2. The proportion of climatic sensitivity scores that are the result of winter and early spring factors (maximum possible score = 20) versus summer factors (maximum possible score = 16). **Sa** = *Sorex arcticus* **S c** = *Sorex cinereus* **Sf** = *Sorex fumeus*; **S g** = *Sorex gaspensis* **Sd** = *Sorex dispar*, **S p** = *Sorex palustris*, **S h** = *Sorex hoyi*; **Bb** = *Blarina brevicauda* (After Herman & Scott 1992)

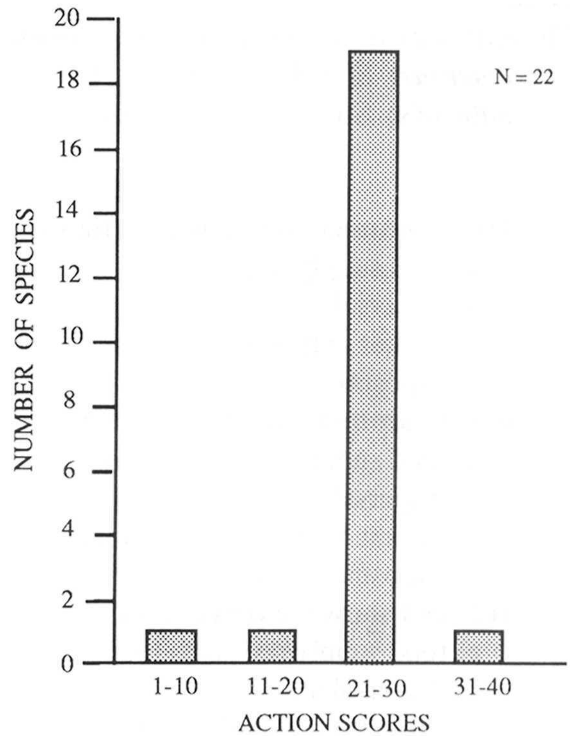

FIGURE 3. Frequency distribution of Action Scores (the total of knowledge and management scores) for Nova Scotian amphibians and reptiles. (From Herman & Scott 1992)

be more susceptible to drying, but we have insufficient data on the distribution of the factors affecting non-breeding animals.

Blanding's turtle *Emydoidea blandingi* is a northern species with a distribution centered in the Great Lakes region. Disjunct populations occur at the edges of the range, particularly to the east and the most isolated of these is confined to the area of Kejimkujik National Park in southwestern Nova Scotia. The species occurs at low densities over much of its range. The Nova Scotia population, which is restricted to an inland plateau characterised by relatively high summer temperatures, is considered to be a relict from a warmer climatic period and may have been spatially isolated for several thousand years. However, the species has one of the lowest critical thermal maxima of any turtle (Hutchinson *et al*, 1966), and so appears to have fairly narrow temperature tolerance. In Nova Scotia the population is confined to highly coloured acidic water bodies and has specific substrate and exposure requirements for nesting sites. Sex ratios of hatchlings are temperature-dependent and could be skewed by insolation increases. The exacting biophysical requirements of the species, in combination with the small population size in Nova Scotia (probably <200 adults) (Power, 1989), makes it particularly vulnerable to changes in water level or insolation, both of which are likely to accompany climate change. Because the species is long-lived, adaptations to climate change in the short term (30-50 years) must be behavioural rather than genetic.

The arctic shrew *Sorex arcticus* had the highest climatic sensitivity score of any Nova Scotian mammal. This shrew is tied to a relatively rare and fragmented habitat at the terrestrial/aquatic ecotone, consisting mainly of low-lying floodplain wet meadows and marsh margins. These habitats are particularly susceptible to increased winter and early spring flooding. In Nova Scotia this shrew appears to be virtually incapable of invading adjacent habitats, making it highly vulnerable. The total general vulnerability score of *S. arcticus* may actually be conservative since there is some evidence that Maritimes populations, which are widely disjunct from those in the rest of North America, constitute a separate species (van Zyll de Jong, 1983). If true, this would increase the taxon's systematic and total scores. Interestingly, 5. *arcticus* is not the rarest of our shrews; *Sorex dispar* (five specimens known) (Scott & van Zyll de Jong, 1990) and *S. gaspensis* (11 specimens known) (Scott, 1988) are far rarer, but had the lowest climatic sensitivity scores of any shrew species. This is because they are restricted to steep talus slopes that will be virtually unaffected by reduced snow cover and increased winter/spring flooding.

Although we have not finished developing our matrix for evaluating birds, we did look at factors that are likely to be important for two migrant species differing widely in their ecological requirements: piping plover *Charadrius melodus,* an endangered wading shorebird, and blackpoll warbler *Dendroica striata,* a small insectivorous forest passerine.

Piping plovers are on the Endangered Species List in Canada and the United States (Erskine, 1992). They nest on gently sloping freshwater and marine sand and gravel beaches from the prairies of southern Canada and northern U.S.A. to the Atlantic coast from Newfoundland to the Carolinas. In 1987, an estimated 48-54 pairs bred in Nova Scotia (Flemming *et al.,* 1988). Eggs and young are extremely susceptible to mortality from recreational use of beaches, particularly pedestrian and vehicular traffic. Predicted sea level rises (0.5- >1.5 m) associated with global warming (Titus, 1989) will inundate those nesting beaches that are backed by high ground. Concurrent creation of new beaches may not be rapid enough to replace those lost.

Blackpoll warblers range across North America in boreal coniferous forest habitats. In Nova Scotia their breeding is confined to coastal white spruce forests on the eastern and northern mainland, and the balsam fir forests on the upper slopes of the Cape Breton Highlands. They are relatively abundant in the restricted habitat in which they occur in Nova Scotia. The most recent population estimate is 6,100 ± 1,300 breeding pairs (Erskine, 1992). Although they are probably not directly susceptible to changes such as reduced summer rainfall and warmer temperatures, they will inevitably be affected when the boreal forest habitat, on which they depend, has shifted north of the St Lawrence River (Hengeveld, 1991).

Although these two bird species face an uncertain future in Nova Scotia, both are readily capable of moving long distances to colonise newly available habitat. This gives them an option unavailable to terrestrial mammals, reptiles and amphibians.

3.3 Vulnerability assessment and management issues

Once the appropriate matrices have been generated, they have to be interpreted and subsequently integrated into a management plan. This process is not always straightforward. The matrix scores may be ambiguous; a group of species with high total scores may have high scores for very different reasons and the differences have to be examined and understood. In addition, since the action scores for most faunal groups will be high, especially in tropical regions, the problem of allocating management resources becomes critical and difficult. Species deserving attention can only be determined from a careful examination of individual scores for each parameter in the biological and climatic sensitivity matrices.

This scheme is scale-independent in both geographic and taxonomic terms; it can be applied on a continental or very local scale, and can be used to address vulnerability of higher taxonomic groups or species assemblages. However, its utility and accuracy is probably directly related to the magnitude and/or speed of the environmental change, since responses to subtle or very gradual changes are much more difficult to assess. Thus, it should be especially valuable for assessing local vulnerability to extinction in protected areas surrounded by disturbed or highly modified landscapes. Whether the causes of change are global, regional or local, these areas, most of which are small and have high edge-to-interior ratios, will respond most rapidly and their biota will be at greatest risk.

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Appendix 1.

The general vulnerability scoring scheme of Millsap *et al.* (1990), as modified for Nova Scotia. Our modifications were as follows:

1) We kept their **Dietary** and **Reproductive Specialisation** variables and substituted a **Habitat Specialisation** variable for their **Other Specialisations;** we also altered the scoring range for all three from 0-3-3 to 0-2-4 (for not specialised, moderately specialised and highly specialised). We added to their two **Reproductive Potential** variables a third one for the average number of reproductive years per female, and adjusted scores so the maximum possible was still ten. We also adjusted the age classes for the age at which females first reproduce.
2) In the **Population Size** and **Range Size** variables we reduced the number of size classes from six to four, though the maximum possible score for each was left at 10. We reduced the range of values in each size class as well, to reflect the fact that Nova Scotia is about a third the size of Florida.
3) In the **Knowledge of population trends** variable we added a category (c); in the Supplemental variables we eliminated two: **Trend in taxon's NS population** (Millsap *et al.* (1990) separated the Florida trend from the overall trend but we restricted the **Population trend** in the biological variables to Nova Scotia); and **Period of occurrence in NS.** We may reinstate the last variable for the bird matrix.

BIOLOGICAL VARIABLES

1. **Population size:** the estimated number of adults in Nova Scotia.
   - a) 0-300 — 10
   - b) 301-3,000, or size unknown but expected to be small — 7
   - c) 3,001-30,000, or size unknown but expected to be moderate — 3
   - d) >30,000, or size unkown but expected to be large — 0

2. **Population trend:** the overall change in number of individuals within taxon's range in NS within last 20 years. If direct data are unavailable, indirect data (such as habitat loss) can be used.
   - a) population size known to be decreasing — 10
   - b) trend unknown but population size suspected to be decreasing — 8
   - c) population formerly experienced serious decline but is presently stable or increasing — 6
   - d) population size stable — 4
   - e) population size suspected to be increasing — 2
   - f) population size known to be increasing — 0

3 **Range size:** the size of the area within NS over which taxon is distributed when distribution is most seasonally restricted. (maximum = 57,000 km^2).
   - a) < 200km2 (<0.35%) — 10
   - b) 201-2,000km2 (0.35-3.5%) — 7
   - c) 2,001-20,000km2 (3.5-35%) — 3
   - d) 20,001-57,000km2 (35-100%) — 0

4. **Distribution trend:** % change (since European settlement) in areas of NS occupied by taxon. High values reflect significant range fragmentation.
   - a declined by 90-100% — 10
   - b) declined by 75-89% — 8
   - c) declined by 25-74% — 5
   - d) declined by 1-24% — 2
   - e) stable or has increased — 0

5. Population concentration: the degree to which individuals in the population concentrate or aggregate seasonally or daily (hibernacula, roosts).
   - a) majority concentrates at a single location — 10
   - b) concentrates at 2-25 locations — 6
   - c) concentrates at more than 25 locations — 2
   - d) does not concentrate — 0

6. **Reproductive potential for recovery:** the ability of the taxon to recover from serious population declines.
   - **A)** Average no. of eggs or live young produced per female per year.
     - a) <1 per female per year — 3
     - b) 1-9 per female per year — 2
     - c) 10-100 per female per year — 1
     - d) > 100 per female per year — 0
   - **B)** Minimum age at which females typically first reproduce.
     - a) > 8 years — 3
     - b) 3-8 years — 2
     - c) 1-2 years — 1
     - d) < 1 year — 0
   - **C)** Average number of reproductive years -per female.
     - a) < 1 year — 4
     - b) 1-3 years — 3
     - c) 4-10 years — 2
     - d) 11-30 years — 1
     - e) > 30 years — 0

7. **Dietary specialisation,** including specialisation in foraging space or substrate, prey type, prey size or prey behaviour.
   - a) highly specialised — 4
   - b) moderately specialised — 2
   - c) not specialised — 0

8. **Reproductive specialisation,** including specialised requirements for breeding sites and/or conditions for rearing young.
   - a) highly specialised — 4
   - b) moderately specialised — 2
   - c) not specialised — 0

9. **Habitat specialisation,** including dependence on special moisture regimes, plant/animal communities, or on special habitat structure or physiography, such as talus formations.
   - a) highly specialised — 4
   - b) moderately specilised — 2
   - c) not specialised — 0

ACTION VARIABLES

1. **Knowledge of distribution** in NS (*survey score*)
   - a) distribution is extrapolated from a few locations, or knowledge limited to general range maps — 10
   - b) broad range limits or habitat association known but local occurences cannot be predicted accurately — 5
   - c) distribution is well known and occurence can be accurately predicted throughout the range — 0

2. **Knowledge of population trends** in **NS** (*monitoring score*)
   - a) not currently monitored — 10
   - b) monitored locally intermittently — 7
   - c) monitored intermittently province-wide or regularly locally — 5
   - d) monitored regularly province-wide without statistical sensitivity — 3
   - e) monitored regularly province-wide with statistical sensitivity — 0

3. **Knowledge of factors limiting populations** in NS, including inference from data on non-NS populations (*research score*)
   - a) factors affecting population size and distribution are unknown or unsubstantiated — 10
   - b) some factors affecting population size and distribution are known but one or more are unknown — 5
   - c) most major factors affecting population size and distribution are known — 0

4. **Present management activities** in NS (*management score*)
   - a) none directed entirely or primarily at the taxon — 10
   - b) management mostly related to conservation of populations or habitats — 5
   - c) some direct management in addition to enforcement of conservation law — 0

SUPPLEMENTAL VARIABLES

1. **Systematic significance** of the taxon (select all applicable categories)
   - a) monotypic family — 4
   - b) monotypic genus — 3
   - c) monotypic species — 2
   - d) disjunct population below the species level — 1
   - e) no significance — 0

2. **Percentage of taxon's total range** that occurs in NS
   - a) 51-100% of total range in NS — 5
   - b) 26-50% of total range in NS — 4
   - c) 16-25% of total range in NS — 3
   - d) 5-15% of total range in NS — 2
   - e) <5% of total range in NS — 1

3. **Harvest of taxon** in NS
   - a) harvested without legal protection — 4
   - b) harvested under regulation — 3
   - c) harvested by accidental take or by killing of nuisance animals — 2
   - d) harvest prohibited by regulation — 1
   - e) no harvest — 0

Sensitivity of NW European species and ecosystems to climate change and some implications for nature conservation and management

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Summary

The average global temperature has increased by about 0.75°C since 1850 and, if the climate models are correct, future warming will proceed even faster. In the more distant past, species and entire ecosystems have responded to less dramatic climate fluctuations. This would imply that "modern" species (and ecosystems) are probably already responding to the ongoing changes in temperature, and associated environmental changes such as water availability, and that future responses are likely to be even more significant.

This paper gives examples of the climate-sensitivity of some selected plant and animal species, with emphasis on the situation in continental NW Europe. It is suggested that these species could be used as bioindicators to detect and monitor ongoing changes in natural ecosystems in relation to the enhanced greenhouse effect.

Some conclusions are also drawn concerning the possible effects of rapid climate change on nine major types of ecosystems and landscapes in NW Europe, followed by a discussion of the possible implications for their conservation and management.

One conclusion of the paper is that assessment of the impact of ongoing and future climate changes on species and ecosystems is seriously hampered by the lack of systematic monitoring data on distribution, phenology and other important response factors which determine the sensitivity of species for the enhanced greenhouse effect. The lack of this data makes trend analysis and predictions concerning the implications of global warming for nature conservation and management most difficult.

The paper therefore concludes with some recommendations for future research and stresses the need for rapid establishment of systematic monitoring programmes of selected species and habitats.

1. Introduction

Since 1850, the average global temperature has increased by about 0.75 °C (Boden *et al.*, 1992; Houghton *et al.*, 1992), and, if the climate models are correct, future warming will proceed more rapidly than in any warming period since the last ice age (see Table 1)

It is well documented that species and entire ecosystems have responded to changes in climate in the more distant past (Baker, 1983; Bernabo & Webb, 1977; Birks, 1990; Butzer, 1980; Davis, 1983; Flohn, 1979, Huntley, 1991, Muller, 1979; Peters & Darling, 1985)

Table 1.
Observed and expected temperature changes in Europe and N.America

Time frame/period (years before present)	**Warming °C**	**Rate** in °C/century
15.000 (last glacial) ↓ 11.500 (Allerod)	10	0.3
10.500 (Younger Dryas) ↓ 7.000 (climatic optimum)	7	0.2
5.000 ↓ 2.500	4	0.2
150 ↓	0.75	0.5
Present ↓ Next 100 years	1.5-4.5	3

In general, during warming, species colonised new habitats toward the poles, while often their ranges simultaneously contracted away from the equator (Peters & Darling, 1985). There are also many examples of correlations between the distribution of "modern" species and one or more climatic parameters such as temperature, precipitation or duration of snow-cover (see: Willmanns, 1985; Koning, 1991; Hintikka; 1963). These correlations are both direct and indirect through changes in competitive ability.

It is therefore quite likely that many species are already responding to the ongoing global warming and associated changes in climatological parameters such as precipitation, evapo-transpiration, and frequency of "extreme events" (such as drought, storms, and fire); and that future responses will probably be even more significant.

Predicting what the nature of these responses will be is, however, extremely difficult for several reasons: (a) associated environmental changes, (b) the diversity of response factors and strategies, (c) the complexity of interactions between climate parameters and response factors, (d) the problem of synergism of causes and effects, and (e) the lack of long term observations and monitoring data. These five issues are briefly discussed below.

(a) Associated environmental changes

In addition to temperature rise, there are many environmental factors which are expected to change simultaneously due to the enhanced greenhouse effect. Associated with a gradual global warming, it is expected that **precipitation patterns** may change. Since precipitation is closely linked to water availability, changes in precipitation patterns could have greater impact on biological communities than temperature changes (Neilson & Wullstein, 1983)

In some areas, higher temperatures could increase **evaporation** which, in turn, would exacerbate regional drying (e.g. Manabe *et al.,* 1981). Estimates for **sea level rise,** resulting from thermal expansion of seawater and melting of glaciers and polar ice caps, vary widely from 70 cm by the year 2100 (Nat. Res. Council, 1983) to more than 2 m (Hoffman *et al.,* 1983). If the western Antarctic ice cap melted, which is highly uncertain, rises of up to 5-6 m might occur over the next several hundred years (Nat. Res. Council, 1983). Global warming may alter the **ocean's vertical circulation,** causing changes in the upwelling patterns and **ocean currents** that sustain many marine communities. Increased **atmospheric CO_2** may change photosynthetic efficiencies in plants, in combination with increases in other greenhouse gases, this may result in more acidic, nutrient poor soils.

(b) Diversity of response factors

Certain **physiological processes** are quite sensitive to changes in temperature and humidity. Changes in CO_2, raised temperatures, and changes in humidity and soil moisture will have direct effects on the physiology of plants and animals, notably photosynthesis by green plants, and, to a lesser degree, respiration. As earlier studies have proven, **phenological events,** such as foliation, flowering time, seed-setting, and timing of migration are strongly correlated with climatic conditions and responses occur to climate changes within a relatively short period of time (5-7 years). Thus, if climate change is taking place, changes in phenology should already be detectable (Koning, 1991). Table 2 presents possible changes in flowering times of several plant species in The Netherlands (NL), United Kingdom (UK) and Norway (N). Changes in

Table 2.
Number of days of earlier onset of flowering of some species in Europe as a result of temperature rise, based on calculations of heatsums

	Average date of flowering			expected dates of flowering			number of days earlier flowering		
Country ⟶	NL	UK	N	NL	UK	N	NL	UK	N
Species									
Corylus avellana	25/2	1/2	23/3	11/2		11/2	14		37
Tussilago farfara	20/3	27/2	10/4	27/2	13/2	2/3	23	14	39
Anemone nemorosa	7/4	22/3	11/4	11/3	1/3	3/3	27	21	39
Chrysanthemum leucanthemum	22/5	20/5	16/5	26/4	18/4	18/5	26	32	29
Alnus glutinosa	10/3		14/3	10/2		11/2	20		33

flowering time differ for each country, partly because temperature changes are expected to differ regionally. The GISS scenario was used to estimate the temperature changes per region.

Disturbance of the balance between climate and the life cycle of plants and animals will also have implications for **food-chains and other inter-specific interactions.** Changes in phenological events as described above, may lead to changes in plant-animal relations, such as pollination, and may influence the availability of food to herbivores and disturb plant-parasite-relations.

Because of physiological and phenological responses, in combination with changes in interactions between species, climate change will influence the (relative) **abundance and distribution** of most species. This is illustrated with numerous examples from the past.

(c) Interactions between climate parameters and response factors
The amount of environmental changes associated with a rise in temperature (a) in combination with the large number of possible response factors (b) makes it quite difficult to determine the "final" effect of climate change on natural ecosystems and wild species. Understanding the relationship between the various response factors and climate conditions is important in order to be able to select useful bio-indicators to detect and monitor the effects of ongoing and future climate change on ecosystems and species. Many interactions between species and climate are still not well understood and much more research in this field is needed.

(d) Synergistic effects
To make matters still more complicated, the individual responses of species, in combination with direct effects of climate-related changes in the environment (such as erosion), will influence the structure and functioning of entire ecosystems. Most ecosystems are already suffering from other types of anthropogenic stress (such as pollution and species-introductions) which makes it difficult to separate the "climate-signal" from other causes for observed changes in the natural environment.

(e) Lack of long-term monitoring data
The problems outlined above in assessing the possible effects of climate change on natural ecosystems and wild species makes long term monitoring quite essential. A major problem in assessing the impact of the present changes in climate on ecosystems and species is the lack of long-term field observations during the last century. Data on abundance, distribution and phenology of species from the last 150 years are rather sparse and unevenly distributed, both in terms of geographical coverage and coverage of taxonomic groups. Unfortunately, many long term observation programmes stopped in the sixties as interest in this type of research lapsed. Information on changes in phenology over the last thirty years, the period in which atmospheric CO_2 has risen rapidly, is therefore now largely missing.

To make trend analyses possible, current and future monitoring efforts should be improved. These trend analysis should be based on appropriate bio-indicators, and some important factors to be considered when selecting bio-indicators are discussed in more detail by Ketner & de Groot (1991).

2. Some examples of climate sensitive species in NW Europe

Depending on their response to the combination of factors which have been described in the introduction, the distributional range of species may expand or contract, or changes may occur in their abundance (increase/decrease) within their present range.

For species with a southern distribution, which currently reach their northern limit in NW Europe, it may be expected that they will move northwards. Particularly responsive will be the thermophilous species while species with several life cycles a year will be advantaged by the expected lengthening of the growing season. Many of these species are rather "aggressive", and weed-problems and insect-plagues may increase, both within their present range of occurrence and in newly invaded areas. Some subcontinental species may spread westwards along river valleys. Several of these ruderal species are already on the increase, both within their present range and through expansion of their distribution. This increase is to a large extent the result of human activities, but may be very much accelerated by climate change.

Other species which may decline or retreat as a result of climate change, especially those with a boreal, boreal-alpine or boreal-atlantic distribution. Higher summer temperatures and drought may cause die-back of these species at the southern edge of their distribution in NW Europe.

Information on the direct threat of climate change to individual species is still scarce. There are three types of species that seem most sensitive to rapid climate change: species or taxa that are already rare and/or threatened; specialised species; and those with poor dispersal ability (Peters & Darling, 1985; McNeely, 1990; Huntley, 1991).

To detect the effects of ongoing climate changes "in the field" it is necessary to identify those species which are most sensitive. Selection of sensitive species may be based on paleo-ecological research but may also be deduced from research on the relationship between climate parameters and certain species-characteristics such as physiology, phenology, food chain interactions and population dynamics. Some species or groups of species which may serve as bio/indicators for detecting the effects of climate change are listed below, with emphasis on NW Europe.

2.1 Plants as bio-indicators for climate change

Plants in general are an indicator of climate change since their distribution and life-cycle is quite strongly determined by climatological factors such as temperature and precipitation (water-availability). The following sections briefly reflect on the climate-sensitivity for some types of plants, notably C_4 species (mainly herbs), aquatic plants, woody species, and trees.

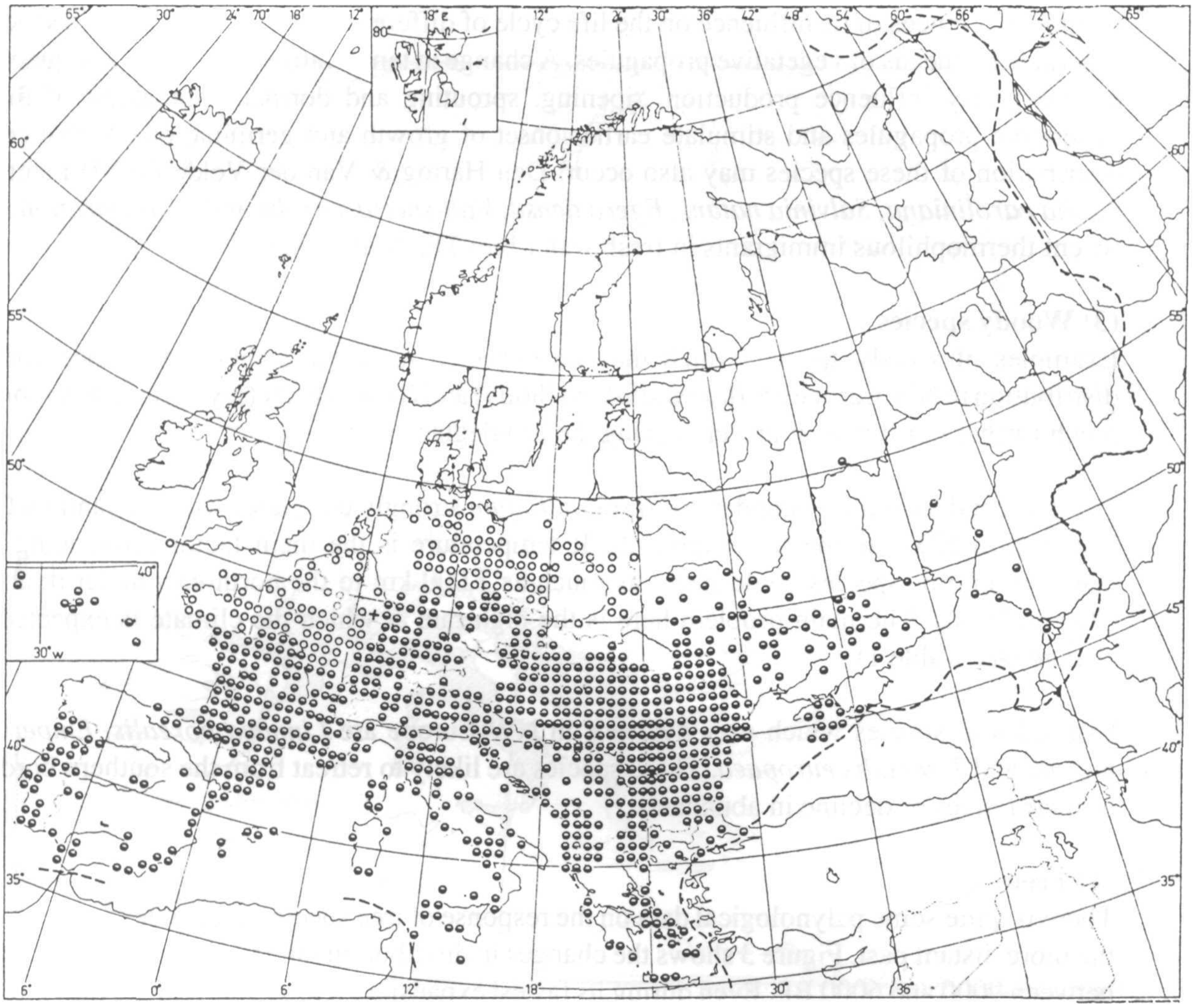
(1) C_4 plants, mainly herbal species

A competitive group of species which might take advantage of a temperature rise are the C_4 species. In Europe the abundance of C_4 species is strongly correlated with temperature and, to a lesser extent, negatively correlated with precipitation (Collins & Jones, 1986). Today, C_4 plants constitute a small percentage of the local floras, and many are not native. In some countries C_4 species are already showing atendency to increase in abundance and change in distribution range (see Table 3).

Table 3.
Preliminary list of species showing a tendency to increase in abundance in the Netherlands and/or Belgium

Family :	Species:	L	T	K	N	Remarks:
	C_4-species:					
Amaranthaceae	Amaranthus blitoides	t	7	7	7	alien
	Amaranthus retroflexus	t	9	7	9	N.Amer., subcosm.
Portulacaceae	Portulaca oleracea	t	8	3	7	trop.
Cyperaceae	Cyperus esculentus	g	-	-	-	trop.
	Cyperus fuscus	t	6	4	4	
Gramineae	Cynodon dactylon	g,h	7	3	5	subcosm.
	Digitaria ischaemum	t	6	4	3	temperate
	Digitaria sanguinalis	t	7	3	3	subcosm.
	Echinochloa crus-galli	t	7	5	4	subcosm.
	Eragrostis minor	t	7	5	4	trop., warmtemp.
	Eragrostis pilosa	t	7	3	?	trop., warmtemp.
	Setaria glauca	t	7	4	6	subcosm., warmtemp.
	Sorghum halepense	t	-	-	-	S.Eur., trop.

Figure 1.
Distribution of *Portulaca oleracea* (purslane) in NW Europe



●: established   o: occasionally   Source: Atlas Flora Europaea

An example of a C_4 species which may create a weed-problem in NW Europe is *Portulaca oleracea* (purslane). Purslane is a herbal species which is at present adventitious in NW Europe (open circles in Figure 1), but may increase its abundance rapidly once the climate becomes favourable.

It should be noted that in the past decades there has been a major expansion in range and abundance of many species with a "weedy" character, both annuals and perennials. This is mainly attributed to human actions related to land use changes. However, it is curious to note that those species which show a tendency to expand are predominantly species with high temperature requirements, that is species with an Ellenberg-indicator value of 7 (see Table 3). Today these species mainly have a Mediterranean/sub-Mediterranean or subcontinental distribution. Although it is still too early to attribute their observed spread in a northerly direction to a rise in temperature, this phenomenon is precisely what may be expected as a consequence of climate change.

(2) Aquatic plants
Another sensitive group of species is the aquatic plants (Brock & Viersen, 1990). Temperature is likely to influence the composition of aquatic macrophyte-communities because of fundamental differences in its influence on the life cycle of different species. Many aquatic species hibernate by means of vegetative propagules. A change in temperature (and quality or quantity of light) may influence production, ripening, sprouting and dormancy-breaking of these vegetative propagules and stimulate earlier onset of growth and germination. A change in distribution of these species may also occur. Den Hartog & Van der Velde (1987) mention *Azolla caroliniana, Salvinia natans, Egera densa, Vallisneria spiralis* and *Pistia stratiotes* as recent thermophilous immigrants in fresh water into The Netherlands.

(3) Woody species
Examples of woody species which may be expected to increase their abundance and/or distribution in NW Europe *are I lex aquifolium* (holly) and *Hedera helix* (ivy), which were found much further north than at present during the last deglaciation.

The present distribution boundary of *Ilex aquifolium* strongly correlates with the January 0°C isotherm in NW Europe (see Figure 2). If temperature is the main factor influencing the distribution, this species could move as much as 1,000 km to the north-east under doubled CO_2conditions. The main problem here is the high rate at which the climate is expected to change (see Table 1)

Examples of species which may decrease in NW Europe are *Linnaea borealis, Empetrum nigrum* and *Trientalis europaea.* These species are likely to retreat from the southern borders of their ranges or decline in abundance.

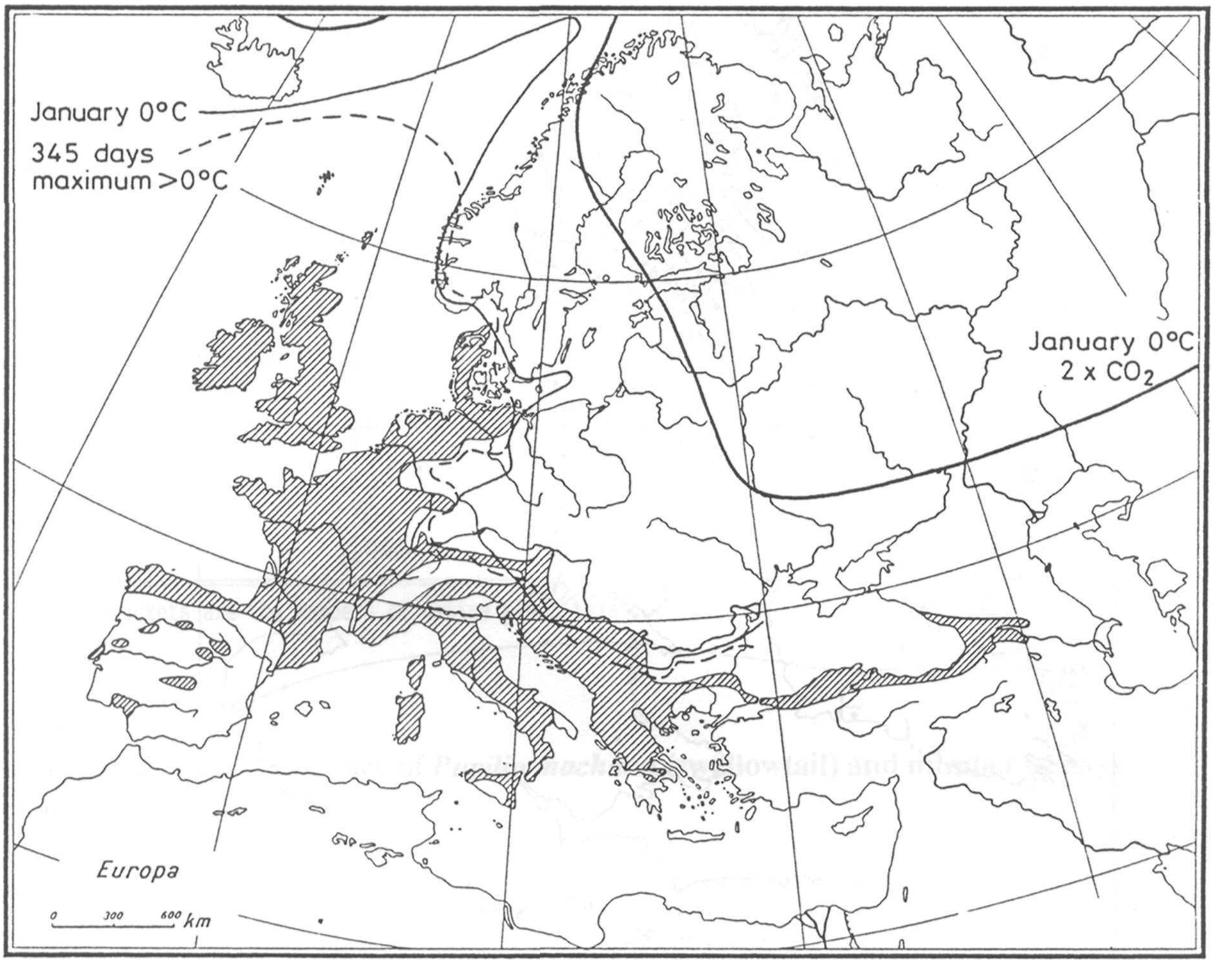
(4) Trees
There is quite some palynological data on the response of tree species to changes in climate in the more distant past. Figure 3 shows the changes in distribution range of the oak in the period between 9000 and 6000 BP. Even during its fastest expansion, it took 500 years to move about 200 km, which means an average migration-speed of 40 km/century.

Sugar maple *(Acer sachharum),* hickories (*Carya* spp.), oaks (*Quercus* spp.), and elms (*Ulmus* spp.) spread northwards rapidly in eastern North America during the postglacial early Holocene. Chestnut (*Castanea dentata*), spread much more slowly, apparently because its self-sterility made it difficult to establish by seed (Davis, 1983).

Table 4 gives some observed migration rates for several species based on palynological data.

A good example of a "modern" causal relation between the limits of distribution and a climate parameter is found in *Tilia cordata.* This species does not set seeds at its northern distribution limit in Britain because pollen-tube growth is hampered by low summer temperatures. With higher July temperatures (flowering season of *Tilia cordata*) the present trees may start to produce seeds and the species may begin dispersing northwards as a result of climate change.

Figure 2.
Distribution of holly (*Ilex*) in NW Europe in relation to the January isotherm

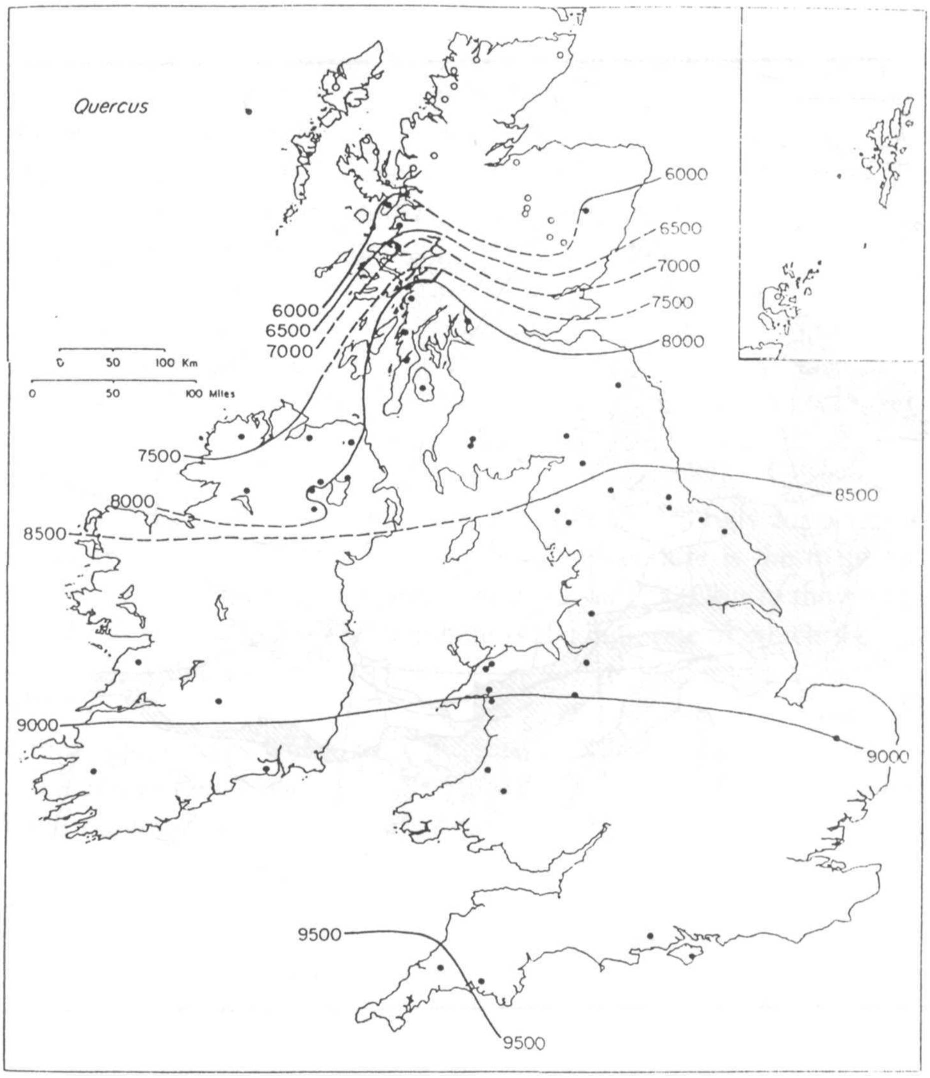


That a tree species may react relatively rapidly to changes in temperature was demonstrated by Kullman (1983) for *Betula pubescens* at its altitudinal borders in Sweden. He found an increase in altitude of the limit of *Betula pubescens,* which he could relate to the increased frequency of warm summers which favoured seedling establishment.

A contrary response, i.e. seedling mortality, may be expected with *Pinus sylvestris* in most of its range in NW Europe. This species slowly declined at a marginal site in Sweden during the little Ice Age (1300-1850). Because of a change in temperature, its regenerative capacity declined and there was a high mortality amongst young trees (Kullman, 1983).

Thus, based on historic (palynological) data and information on the life-history, it is possible to select certain tree-species which may be expected to show a rapid response to climate change in NW Europe.

Figure 3.
Rate of migration of the oak in UK between 9000 and 6000 BP



2.2 Insects, notably butterflies

Of the insects, butterflies are an especially useful group of indicators because there is a relatively large amount of information on their distribution, notably in The Netherlands and the UK (UK Climate Change Impact Review Group, 1991). Another advantage is that there are few species of butterfly, most of which are easy to identify and therefore relatively easy to monitor.

In addition, there is a strong correlation between butterfly distribution and abundance with the vegetation (co-evolution) and, most importantly, there is a strong correlation with climate-variables (notably temperature and humidity). For example, van Swaay (1990) made an analysis of the correlation between the maximum temperature in the summer and the abundance of *Papilio machaon* (swallowtail) over a period of 80 years. Figure 4 shows a significant correlation, with an increased abundance during a warmer period around the 1940s and a reduced abundance during a colder (and wetter) period in the 1960s.

Table 4. Range of observed migration rates of 16 plant taxa in Europe

Taxon*		Range of observed migration rates (m/year)
1 *Fraxinus ornus*	(1)	25 - 100 -200
Abies	(6)	40 - 50 - 300
3 *Castanea sativa*	(1)	200 - 300
4 *Fagus*	(2)	200 - 250 - 300
5 *Pistacia*	(3)	200 - 300
6 *Juglans*	(1)	400
7 *Tilia*	(4)	50 - 130 -300 - 500
8 *Picea*	(2)	80 - 240 -500
9 *Fraxinus excelsior*	(3)	200 - 500
10 *Quercus* (deciduous)	(3)	75 - 150 - 200 - 500
11 *Carpinus betulus*	(1)	50 - 100 - 200 - 300 - 700 - 1000
12 *Ulmus*	(5)	100 - 200 - 500 - 1000
13 *Acer*	(13)	500 - 1000
14 *Corylus*	(4)	1500
15 *Pinus*	(10)	1500
16 *Alnus*	(4)	500 - 2000

* Numbers in brackets are the numbers of native plant taxa contributing to the pollen data

Figure 4.
Correlation between abundance of *Papilio machaon* (swallowtail) and number of days with a maximum above 20°C

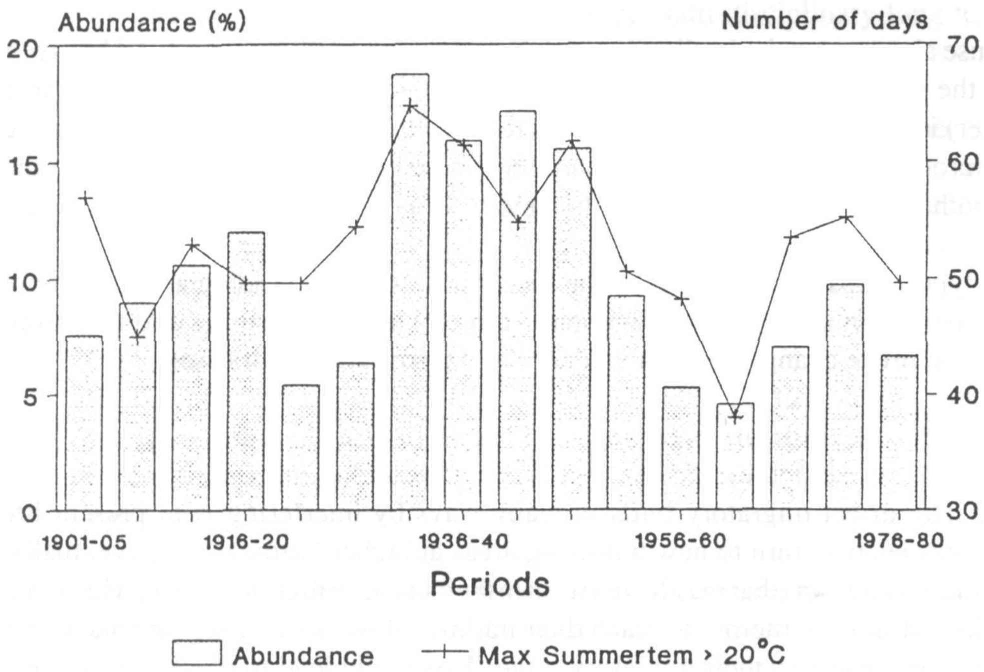
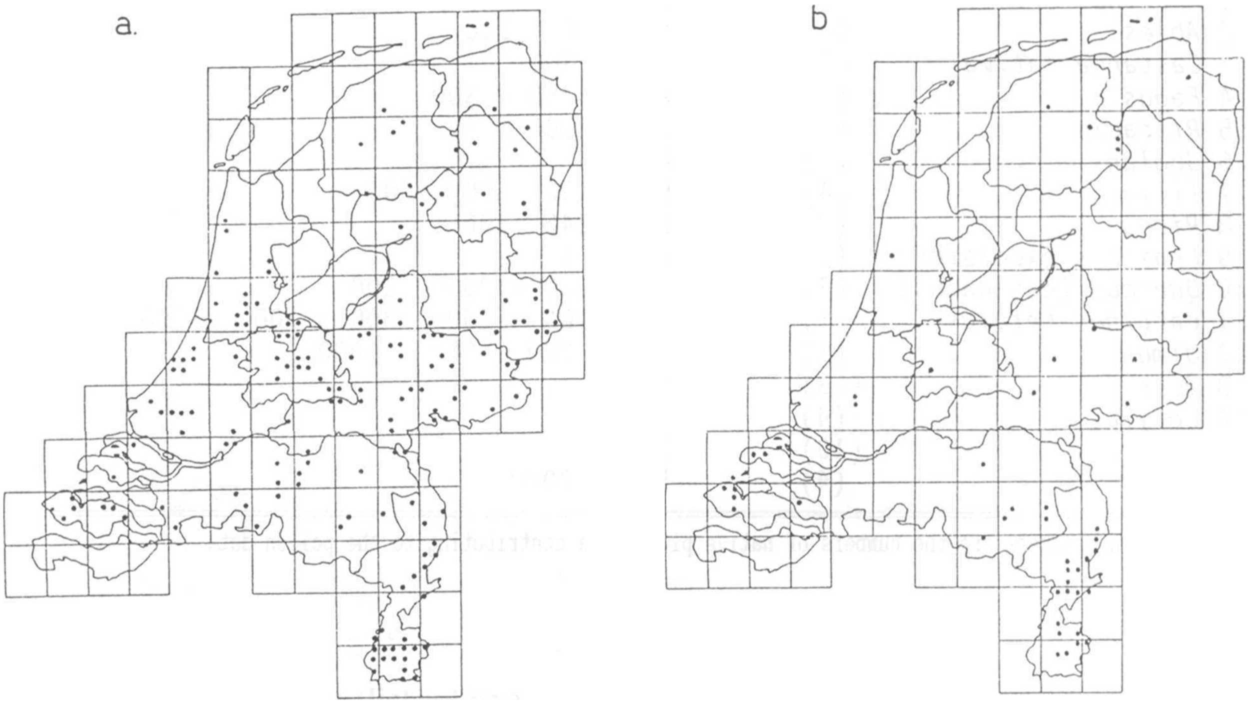


Figure 5.
Changes in distribution of *Papilio machaon* (swallowtail) in The Netherlands
Distribution in the relatively warm period between 1930 and 1950 was wider than in the cold and wet 1960's when the species was limited to the warmest parts.



This same response also appears in the distribution: during the relatively warm period between 1930 and 1950, the swallowtail was widely distributed in the Netherlands, when it became colder (and wetter) in the 1960s its distribution was reduced to a few locations which had the most suitable micro-climate (Figure 5). There are now indications that the species is on the increase again, both in abundance and distribution (Van Swaay, pers.comm.).

It is exactly this type of observed changes in the recent past which should be analysed more detailed in order to distinguish direct human impact (through land use changes and pollution) from the effects of climate change on the abundance and distribution of species.

2.3 Migratory birds

Climatic change may affect migratory birds in many ways by interfering with present life strategies. Some species may turn to new wintering areas at higher latitudes and, eventually, remain north of impassable gaps that may have arisen in their present migratory route. However, many species will continue to attempt to reach their traditional wintering sites, in spite of the barriers that may have arisen on their migratory route. This might lead to drastically smaller populations. Probably the greatest impact will be on birds which depend on freshwater wetlands (especially in the Mediterranean), because these wetlands are threatened by desiccation through changing precipitation patterns and higher evapotranspiration (Meekes, 1992).

Some migratory species that might decline in NW Europe are the Arctic geese (*Branta* spp., *Anser* spp.), waders (*Calidris* spp., *Limosa lapponica),* reed inhabiting warblers (*Acrocephalus* spp.) and crakes (*Porzana* spp.) (Meekes, 1992). Wader species which depend on few stopover sites like the bar-tailed Godwit *Limosa lapponica* and the knot *Calidris canutus* (Smit & Piersma, 1989), may loose vital staging areas, which would considerably hamper their migration. On the other hand, several investigations and records have shown that the migratory behaviour in many bird species is flexible enough for them to shift their migration routes and start wintering at higher latitudes. An example is the blackcap *Sylvia atricapilla* (Berthold & Terrill, 1988).

Northward shifts of southern range borders may also be expected for curlew *Numenius arquata*, whimbrel *Numenius phaeopus*, herring gull *Larus argentatus*, glaucous gull *Larus hyperboreus,* linnet *Carduelis cannabina,* twite *Carduelis flavirostris*, chaffinch *Fringilla coelebs,* brambling *Fringilla montifringilla,* crested tit *Parus cristatus* and Siberian tit *Parus cinctus* (Williamson, 1975; Järvinen & Väisänen, 1979).

3. Sensitivity of NW European ecosystems and landscapes for climate change

The combined effects of the responses (physiology, phenology, species interactions and changes in abundance and distribution) of individual species will lead to overall changes in the structure and functioning of entire ecosystems and landscapes. At this level it is quite difficult to distinguish the effects of climate change from other, synergistic, effects of human activities. To increase our understanding, integrated, multi-disciplinary long term research efforts are needed in selected case study environments.

Based on the above considerations and previous studies (e.g. Ketner & van Huis, 1989; Boer & de Groot, 1990) some possible effects of climate change in various selected climate sensitive ecosystems, landscapes and geographical areas are briefly discussed below. These areas may offer good opportunities to serve as "early warning systems" to monitor the ongoing and future effects of climate change.

(1) Coastal dunes

Both biotic and abiotic changes can be expected in dune ecosystems as a result of climate change, including changes in relief, ground water fluctuations and changes in soil properties. Coastline erosion, salinisation and fluctuations in water table will mainly result from sea level rise.

Simultaneously, changes in biotopes, ecological zones and biogeographic patterns of plant and animals will occur as a consequence of climate change. Plant species with a predominantly Mediterranean-Atlantic distribution, such as *Mibora minima, Blackstonia perfoliata* and *Lathyrus japonicus,* might invade more northern dune systems (van der Meulen *et al.,* 1991).

(2) Coastal wetlands
Biotic communities in estuaries, saltmarshes and other coastal ecosystems are also at risk under the expected rapid climate change (de Groot & Stortenbeker, 1992).

Many coastal species, like marine mammals and birds, depend on the rich food sources supported by the high productivity of adjacent saltmarshes. Saltmarshes are particularly threatened by the expected increase in sea level rise. It has been calculated that a sea level rise of 20-30 cm would affect 10% of the declared nature reserves in the UK and have negative impacts on invertebrates and birds which inhabit mudflats (UK Climate Change Impact Review Group, 1991). Intrusion of saltwater would be another threat to brackish and freshwater lowlands along the coast.

(3) Inland wetlands and peatlands
The main threat to inland wetlands and peatlands/bogs is a change in hydrological conditions. Both an increase or decrease in water availability would alter the species composition of the communities in these areas. Their sensitivity to desiccation is clearly demonstrated by the effect of human drainage of agricultural lands on adjacent wetlands in the past (de Groot & Stortenbeker, 1992). Climate change could worsen the situation. In Coto Donana (Spain), for example, it has been estimated that desiccation of the inland wetland area has led to the loss of at least a 100 plant species from the area in the last 80 years (van Huis & Ketner, 1987; van Huis, 1989).

Profound impacts of climatic changes on the functioning and distribution of bogs is to be expected because of the close correlation between their geographical distribution and climatic conditions, and their delicate hydrological balance. Suboceanic raised bogs in Ireland, The Netherlands and West Germany are very sensitive to an increase in average temperature and a decrease in summer precipitation (Schouten *et al.*, 1992). Changes in the hydrology and in the chemistry of the upper peat layer, as well as a lowering of the ground water table, will cause an increased decomposition rate and a decrease in peat accumulation.

(4) Riparian ecosystems
Rivers and their associated riparian ecosystems would also be good places to monitor the effects of climate change. They reflect changes in runoff over the entire watershed area which may appear as the occurrence of extremes in river discharge leading to more erratic inundation or desiccation of the riparian ecosystems. Towards the coast, changes in the regime of saltwater may greatly affect the biotic communities both of the rivers themselves and of the bordering vegetation.

(5) Grasslands and arable land
As a result of changed competition and the invasion of new species, a gradual change in the overall species composition in grasslands may occur under warmer climatic conditions. Grass and herb species which are now adventitious or mainly found in ruderal environments may become established in grasslands. C_4 species such as *Portulaca oleracea*, *Cynodon dactylon* and *Cyperus rotundus* form a real threat to established species (Ketner, 1990b).

Also on arable land an expansion of weeds is to be expected, C_4 as well as C_3 species. The characteristic weed communities of arable fields, already very impoverished, may vanish completely. In addition, an increase in weed species will seriously affect agricultural production, causing crop losses and/or increasing use of herbicides at increasing environmental costs.

(6) Forest ecosystems
An important problem with respect to forests would be the differences in response between the canopy stratum and the undergrowth. The species occurring in the understory of the forest will probably respond faster than the trees themselves which would lead to a destabilisation of the entire living community. Exotic thermophilous species, both woody and herbs, will invade the present understory while native species may disappear.

In the case of successive years with extreme events, such as excessive night frost or severe storms, an increase in mortality of trees is likely to occur.

(7) Montane ecosystems
Ecosystems and life communities occurring at higher altitudes are very sensitive to climate warming, mainly because the climatic gradients and associated changes in vegetation patterns occur over short distances.

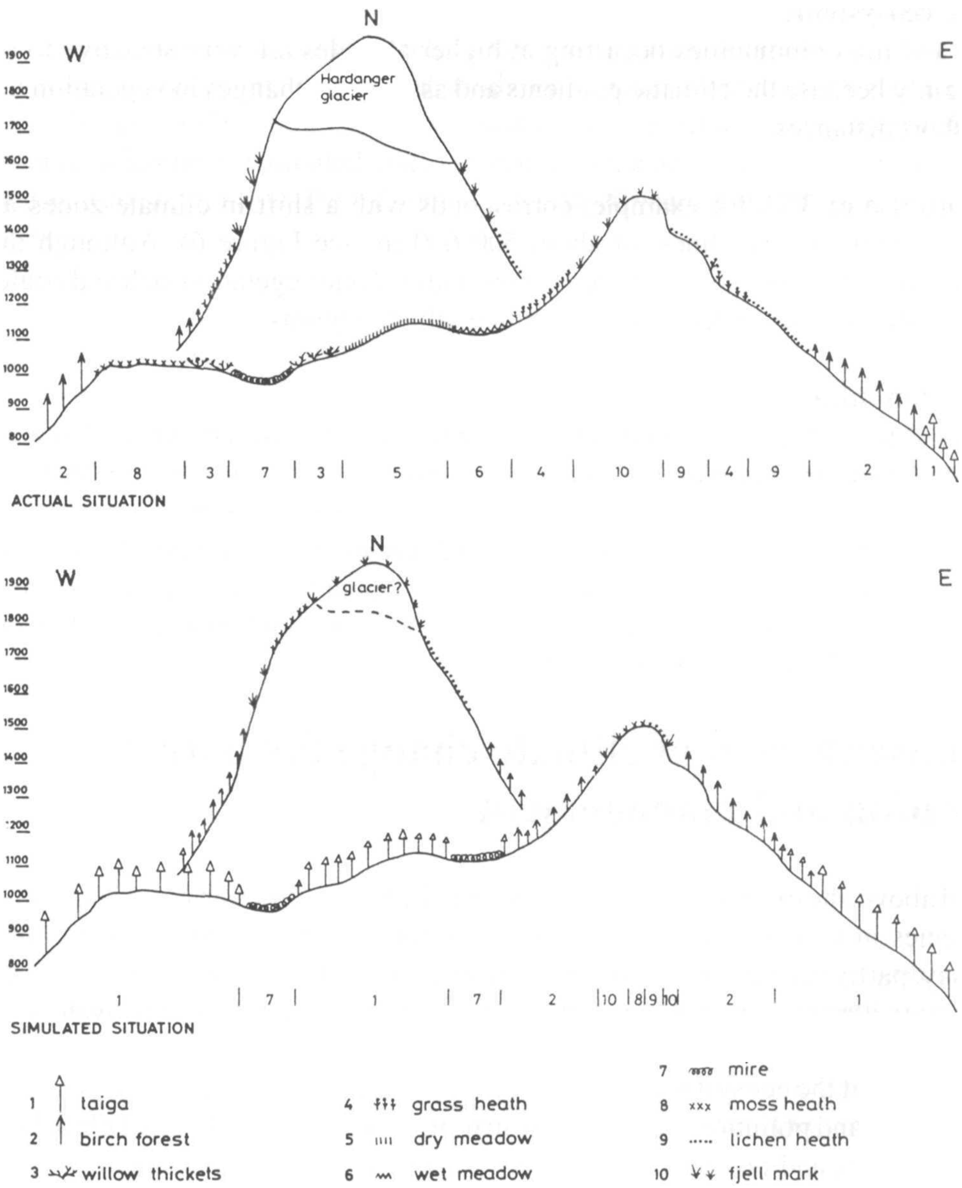
A temperature rise of 3°C, for example, corresponds with a shift in climate-zones and the corresponding snow and tree lines, of about 500-600 m (see Figure 6). Although this is a relatively short distance, it is more than the average width of one vegetation-belt and could mean the disappearance of many species from the higher alpine regions.

(8) Arctic communities
Communities at high latitudes are another example of life zones which may be threatened by climate change. Here temperature rise is expected to be proportionally greater than at lower latitudes (Hansen *et al*., 1986), leading to considerable physiological and competitive stress (Boer & Koster, 1992). At the same time the affected species and ecosystems have no space to retreat. On the other hand, many arctic species have adapted to withstand very large annual fluctuations in temperature and some may therefore be able to tolerate a sizable change in temperature (Peters & Darling, 1985).

4. Some consequences of climate change for nature conservation and management

As discussed above, the expected global warming will influence the distribution and abundance of many species in various ways. What this means for the conservation of these species is difficult to say, partly because many other factors need to be taken into account such as changes in climate-parameters other than temperature (such as precipitation, humidity, water availability, storm frequency, occurrence of lightning and fire), sea level rise, and, most importantly, synergistic effects at the ecosystem and landscape level due to other human influences such as habitat destruction and pollution. Specific information concerning the threat of global warming to individual species and protected areas is still rather fragmentary, possibly owing to these complicating factors. Leemans (1990) compared five scenarios for changes in Holdridge life zones with regard to their implications for nature **reserves.** Under the most optimistic scenario (GFDL-Qflux) at least 16% of the existing reserves will encounter major difficulties concerning the protection of the present life-communities under changed climate conditions. The most pessimistic scenario (UKMO) implies problems for almost 60% of the existing reserves. Although these are very crude figures, they do indicate that there is a real threat to the survival of many life communities in existing reserves and, because of the various time lags involved (both in terms of ecological processes and in the adjustment of human planning and decision-making) measures should be taken long in advance in order to anticipate and mitigate the effects of climate change.

Figure 6.
Schematic cross section of the vegetation zonation on the Hardangervidda plateau, under present climatic conditions and under double CO_2 conditions



4.1. Some aspects to consider in relation to the conservation of threatened species, ecosystems and landscapes in relation to climate change

(1) The rate of change

In the introduction to this paper, Table 1 shows that the expected rate of temperature change in the next 100 years is a factor of 10 higher than the temperature change that occurred during warming periods after the last ice age. Although the magnitude of the temperature change was higher then (10°C), the warming took about 3,500 years or on average 0.3°C per century. A temperature increase of 3°C corresponds with a change in bio-climatic zone of about 600 km. Examples from the past show that changes in distribution have been at most 100-200 km/ century for trees with wind-born seeds (such as elm and maple). For most deciduous trees (walnut, chestnut, oak) migration rates (actual as well as potential) of 10-50 km/century are more typical (Huntley, 1991, see also Table 4).

A shift in bioclimatic zones of 600 km in 100 years is clearly much faster than most plants can migrate, especially in the case of trees. Even "fast" species, such as spruce which may "migrate" up to 200 km/century, would have problems under the expected rate of climate warming.

Although migration rates of certain animals (e.g. migratory birds) may be much faster, they usually depend on certain food plants or other habitat factors (such as shelter, nesting sites) and therefore have to "wait" until favourable circumstances have developed before they can establish. While "waiting", a species may be confronted with increasingly unfavourable circumstances in its present distribution range. Very little is known about the rate of mortality of a species as a result of climate change. What will happen at the southern border of a species which is expected to move northwards? How rapidly will this species die at the southern edge? For species with a narrow distribution range (narrow in the sense of distance north-south) it is crucial that mortality remains low to enable the species to move northwards in time.

(2) The presence of barriers

Barriers which slow down or even prevent adjustment of distribution ranges are another complicating factor. Soil-conditions, for example, will not change as rapidly as the climate, which leads to lag-times in the establishment of plants. For instance, deciduous trees will have difficulty establishing on soils to the north of their present distribution range, which are usually more acidic. Physical barriers such as mountains, open water, and cultivated and urban land, may completely prevent the migration of certain plant and animal species.

From fossil records it is known that a large, diverse group of plant genera had a circumpolar distribution in the Tertiary, including watershield (*Brassenia*), sweet gum (*Liquidambar*), tulip tree (*Liriodendron*), magnolia (*Magnolia*), moonseed (*Menispernum*), hemlock (*Tsuga*), arbor vitae (*Thuja*), and white cedar (*Chamaecyparis*) (Tralau, 1973). During the Pleistocene ice ages, all went extinct in Europe while surviving in North America. The east-west orientation of such barriers as the Pyrenees, Alps, and the Mediterranean very likely blocked their southward migration, which was partly responsible for their extinction

(3) Isolation and landscape fragmentation

Linked to the problem of barriers is the fact that, especially in NW Europe, the landscape has been very fragmented by human activities and most remaining natural ecosystems, and the species within them, have become isolated and reduced to small reserves and other types of protected areas. More information on this aspect can be found in Peters and Darling (1985) and Huntley (1991).

(4) Destabilisation of life communities

The individual response of taxa to climate change will lead to great instability in plant communities and entirely new community assemblages may come into existence. Because of changes in competitive power, as well as changes in environmental conditions, a species may now be able to invade a habitat in which it did not previously occur. Because of this individual species response, it is unlikely that entire communities or ecosystems will shift northwards.

4.2. Some possible management measures to prevent further decline of biological diversity under changed climate conditions

Natural ecosystems, apart from their ecological importance and intrinsic value, provide numerous benefits to human society and the continuing degradation and loss of wilderness areas leads to ever increasing ecological and economic costs (de Groot, 1992).

Rapid climate change will most likely accelerate this process and in order to prevent or at least reduce the further decline of biological diversity it is essential to assess the implications of climate change for nature conservation and management policies. To prevent or mitigate the negative effects of rapid climate change on threatened species and ecosystems, several options for conservation measures should be considered.

(1) Management measures within protected areas

If climate changes as rapidly as is now expected, active management in existing protected areas will be needed to maintain suitable environmental conditions:

- **Water management:** moisture patterns could change which would make adjustment of water management strategies necessary to maintain favourable conditions and allow species to adjust to changing climate conditions. In ecosystems with a high water table, desiccation could become a major problem which could (temporarily) be alleviated by irrigation measures, or by raising the water table. On the other hand, in areas which are subject to increased flooding, draining could be a feasible management option.
- **Pest-control:** changes in food chain interactions and possible invasions may lead to explosions of certain pest species and may cause an increase in the occurrence of certain diseases (e.g. botulism).
- **Management of fire regime:** changing temperatures and humidity could also lead to changes in the (natural) occurrence of fires, as well as the susceptibility of ecosystems to fire. Over time, many communities have adjusted to a certain frequency and intensity of burning. If climate changes too quickly, man may be forced to undertake intensive regulation of the fire-regime to maintain certain habitats, as in the case of ongoing measures taken to maintain the pine-wood habitat of Kirtland's warbler (Leopold, 1978).

(2) Adjustment of siting and zoning of existing protected areas
Another possible measure would be to anticipate climate change through adjustment of the size and form of existing protected areas. Climate will become more erratic and species will need more room to cope with changing environmental circumstances. Obvious advice would therefore be to expand the total size and number of protected areas as much as possible since this would increase the chance that if the climate in one site becomes unfavourable, the species might survive elsewhere. In large reserves, species would have a greater chance of finding suitable micro-climatic conditions or of following the climate by shifting altitudinally or latitudinally.

In order to retain the option of shifting reserve boundaries, zoning around reserves should be flexible. Establishment of buffer-zones with multiple uses would make it possible to shift the core-area of the reserve according to observed climatological changes. Flexible zoning of protected areas would not only be beneficial in view of future climate change but it would also help to reconcile conservation objectives with socio-economic needs and thus, in the long run, make the reserve more viable.

The zoning-system could also help to gradually convert (rehabilitate) adjacent cultivated lands into reserve land in areas where this would be most beneficial, both from an ecological and an economic point of view.

(3) Selection of new protected areas
Since it will not always be possible to expand existing sites, new areas will have to be selected, taking due account of the expected changes in climate.

We should be constantly consider the fact that over the time a rise in temperature has taken place in a particular region, species will not have simultaneously occupied their potential areas of distribution. Two species may reach the same site at different times and rates: species A may occupy its new area after 50 years while species B may take 100 years to do so. It is therefore important to safeguard sufficient refuge areas, with viable populations, from which threatened species can disperse gradually into the new potential areas of distribution.

Selection of sites should focus on areas which have the highest potential to provide suitable habitats for threatened species under changed climatic conditions. In Europe, this will usually be to the north of the current distribution limit of the species involved.

Another approach could be to select those areas with the highest biological (and genetic) diversity in the hope that these areas will serve as "nuclei" (refugia) from which areas that lose many species during periods of rapid change could be recolonised. Often these sites will coincide with ecotones which are transition zones between major biomes or ecosystem complexes (Ketner & de Groot, 1991).

(4) Establishment of corridors and a viable ecological infrastructure
Owing to the isolation of most protected areas, migration and adjustment of distributional ranges will be difficult for most species. Considering the expected speed of future climate changes, there will be little time to adapt to new conditions within the present range, both

behaviourally and/or evolutionarily. Without special measures, extinctions of local populations are very likely to increase. It is therefore essential to improve existing corridors between protected areas, and establish new ones, to allow plants and animals to follow favourable environmental circumstances. This may possibly involve active "nature development" (as it is called in the Netherlands) to rehabilitate degraded areas or re-convert areas which were in use for other purposes (such as agriculture) (Bishoff & Jongman, 1992). What is needed is a viable network of protected areas and functional corridors or connecting landscape elements. One of the positive side effects of climate change issue might be to stimulate the development of a viable ecological infrastructure over large regions, which is especially important in the fragmented European landscape. A recent initiative to this effect was launched by the Dutch government under the name "*Eeconet*" (Bennet, 1991).

(5) Need for artificially aided dispersal / (re)introduction
Since implementing the measures mentioned above will take time, and because these measures may not be successful for all species, it may be necessary to actively transfer certain species to new sites/habitats, or to reintroduce them in areas where they have disappeared as a result of a series of unfavourable climatological events (drought, excessive rain, etc.).

An unusually severe drought, for example, might cause local extinctions in areas where a species ordinarily could survive with minimal management. Such transplantations and reintroductions, particularly involving complexes of species, will often be difficult, but applicable technologies are being developed (Lovejoy, 1985).

5. Conclusions / Some research needs and questions

Knowledge about species and their relation to climate, and thus to climate change, is rather limited. A major problem in assessing the possible impact of climate change on natural ecosystems and species is the occurrence of synergistic effects: man has changed (and still is changing) the natural landscape at such a scale and intensity that it is difficult to distinguish between the effects of climate change and the impact of other anthropogenic environmental changes such as acidification of water and soil, and air pollution.

To increase our understanding of the possible effects of climate change on natural biota, and translate this understanding into practical management and policy making, some research questions and needs are briefly outlined below.

(1) Phenological research and monitoring
There is a large amount of historical phenological data in Europe which needs analysing in relation to local climate changes. Unfortunately the interest in phenology in Europe came to an end in the sixties. It is therefore recommended that a new effort should be made to revitalise this field of research.

(2) Demographic studies (biogeography)
Both ecological studies and monitoring programmes are needed on the explosive invasions of species (including aliens), addressing questions such as: why are they so aggressive?; what triggers their expansion?; how fast do they migrate?

Migration studies of dispersal strategies and dispersal rates for selected species should be strengthened and their use in detecting the effects of climate change assessed. Both long and short distance dispersion should be included. Also knowledge concerning minimum viable populations and critical ecosystem sizes should be improved in view of the expected changes in climate.

(3) Germination studies and transplantation experiments in the field
Improved information is needed on the influence of temperature on dormancy breakage, seed germination and the periodicity of seedbanks.

Also, transplantation experiments with species as well as with intact vegetation-types are needed (Habjorg, 1990), such as those presently being carried out and planned in Norway (Holten & Carey, 1992).

(4) Integrated, multi-disciplinary landscape ecological studies
One of the conclusions of a European conference on landscape ecological effects of climate change (Boer & de Groot, 1990) was that knowledge about the integrated effects of climate change at the landscape level is still rather fragmentary. It is therefore recommended that efforts in this field should be intensified. Integrated landscape-ecological studies should preferably be carried out in selected, climate sensitive areas with a large concentration of climate sensitive species and biotic and abiotic processes. Some options for suitable areas and habitats have been given in this paper. In these areas, favourable opportunities exist to study combinations of the other questions mentioned above. Often, the edges between these ecosystems (or ecotones) are good places for detecting and studying the effects of climate change, since these will be places with a high concentration of range limits of individual species. Unfortunately, no large, intact ecotones are found in continental NW Europe (except in northern Scandinavia).

(5) Laboratory experiments
In addition to field observations, laboratory experiments should be carried out for interpretation and better understanding of the reasons for the changes in distribution. For example: plant growth rates under different temperature regimes, temperature requirements for germination, and ecophysiological experiments with selected plants.

(6) Modelling
The information collected in the field and in laboratory experiments, should be incorporated in modelling experiments. To improve the predictive value of climate impact models, close collaboration between scientists involved in field studies, laboratory experiments and modelling is essential.

(7) Integrated long-term trend analyses and monitoring programmes
Long-term monitoring of environmental changes in the field is essential if we are to find answers to the questions posed above. First of all it is necessary to see what is really happening "in the field" in order to be able to distinguish between the effects of climate change and other anthropogenic environmental changes. Monitoring is also essential to verify the validity of predictions from climate impact models, and to assess the effectiveness of anticipation and mitigation measures. Long-term monitoring programmes should focus on a network of selected sites, indicator species and processes. At the global level, where satellite observations are an important instrument, efforts to monitor environmental change such as the programmes of IGBP and UNEP are increasing. In addition, complementary field programmes are needed at the regional and local level in order to see what is really happening to the species and biotic communities "on the ground". A good example is the network of Long Term Ecological Research (LTER) sites which is being established in the USA.

In Europe, the European Union for Coastal Conservation is launching a long-term monitoring effort focussed on coastal dunes and wetlands. In the UK, an initiative is being started to establish an "Environmental Change Network", a multi-agency, long-term research programme to record, analyse and predict environmental change in the United Kingdom.

An important aim of ongoing and future research should be to provide more and better information on the possible responses of natural ecosystems to global wanning. Simultaneously, large-scale systematic monitoring programmes are badly needed to test the theories which are developed and to provide actual data to improve the predictability of climate impact models.

Since there are considerable time lags involved, both in the response of species and ecosystems to climate change, and in the response of human society, it is essential that information about (potential) effects of global warming on the natural environment is translated into actual planning and management measures as soon is it becomes available in order to prevent further decline in biological diversity in Europe and elsewhere.

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Impacts of climate change on mountain protected areas: implications for management

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Abstract

The threat of global climate change has captured the imagination and concern of people around the world. The issue has brought international attention to the repercussions of the man's activities on the global environment. There is growing consensus among the scientific community that global warming is inevitable. Although timing and severity of such climate change is being debated, considerable basic scientific information is needed in order to understand global climatic processes, particularly the influence of oceans on climate. Current models are not sufficiently precise to predict regional climatic change, let alone account for the influence of topographic features such as mountain ranges. Many scientists predict changes in mountain rain shadow effects, storm frequency and intensity, and periodicity in temperature regimes. There may be increased fire frequency and invasion by insects and other deleterious pests and pathogens. Biological response to climate change in mountainous regions can be expected to first be detected in alpine and sub alpine ecosystems; first and second order streams; rare species populations utilising narrowly defined habitats; ecotones between ecosystems distributed along elevational gradients; and slope/aspect dynamics dictating temperature and moisture regimes.

Unfortunately, climatic thresholds influencing species distribution are rarely known, so the dynamics of future changes are not easily predicted or quantified. The effects of climate change on indigenous people utilising mountain protected areas can be estimated by comparing vulnerable natural resources with resource utilisation patterns of local people.

Land managers of mountain protected areas can take several steps now to prepare for what could be a cataclysmic change to their natural and cultural resources within the next 50 to 100 years. The first step is to conduct sensitivity analyses of vulnerable cultural and natural resources, utilising a panel of experts with the best available first hand knowledge of the area. A second step is to evaluate the distribution and patchiness of protected areas surrounding natural areas.

Identification of movement corridors and the potential edge effects from adjacent land use provides an indication of the limits of biological response to climate change on a landscape scale. A third step is to develop and market in the scientific community a conceptual framework for establishment of a well-targeted monitoring program to detect long-term meteorological changes and the resulting biological and geophysical responses. A fourth step is to initiate programs to salvage vulnerable species that might require a long-term commitment to activities such as genetic research, establishment of a seed bank or captive breeding program, or the establishment of alternative suitable habitat for species introduction. As a final step, the analysis of potential impact on indigenous populations should provide insight concerning the need to initiate gradual adjustments in traditional resource utilisation, such as water and timber use, grazing on high elevation meadows, or use of suitable agricultural crops.

Planning now for such a nebulous event in the distant future requires great courage and vision. Most land managers, however are desperately trying to respond to daily crises without the luxury of being able to plan far into the future.

Introduction

On June 23, 1988, Dr. James E. Hansen, a prominent scientist at the National Aeronautical and Space Administration, testified before the U.S. Senate Committee on Energy and Natural Resources that so-called "greenhouse warming" had in fact begun (Climate Alert, 1988). This public statement galvanised the interests of many governmental and conservation interests in the United States. It contributed to the national debate on environmental issues that were a large part of the presidential election of that year. Since that time, the threat of global climate change has captured the imagination and concern of the world. It has been the focal point of numerous debates on international environmental policy (Response Strategies Working Group, 1990). In 1990, the newly elected U.S. President, George Bush, established a U.S. global change research programme that was developed by the Committee on Earth Sciences (1991). This commitment of over $1 billion per year represented as much money in the first year of the programme as was expended during the entire 1980s to study the phenomenon of acid rain under the National Acid Deposition Assessment Programme. The stakes in terms of the need to better understand this phenomenon are very high, as expressed by an editorial in the newspaper, the *Boston Globe*, on August 10, 1988:

> *"The threat that does not lessen, but grows stronger, is the one posed by the gradual warming of the earth's atmosphere--a climatological phenomenon known as the green-house effect.*
>
> *"Scientists now warn that early in the 21st century—within the lifetimes of most people now alive—temperatures will rise significantly to trigger devastating effects ....*
>
> *"[Solutions] will require international cooperation of a kind never before undertaken or achieved. They also require a degree of political leadership that has rarely been displayed-except in time of national peril."*

There is consensus in the scientific community that global climate will change in the coming decades at a rate unprecedented in human history (Houghton *et al.*, 1990; Schneider, 1989; Hansen & Lebedeff, 1988). Temperature increases are predicted by a variety of general circulation models developed to describe the global climate system (Schneider, 1989).

The main reason for this global warming is a pollutant, carbon dioxide, which results from the burning of fossil fuels (e.g., coal, oil, and natural gas). It also comes from the destruction of forests, which release carbon dioxide into the atmosphere when they are burned or cut down and decomposed. Other "greenhouse gases" which contribute to global warming are fluorocarbons, which also disturb the protective ozone layer in the upper atmosphere; methane (natural gas); nitrous oxide; and ozone in the lower atmosphere (World Resources Institute, 1989). Sample icecaps extracted from glaciers have demonstrated an increase in carbon dioxide, nitrous oxide, and methane over the last century (Watson, 1990). It is estimated that approximately six billion tons of carbon dioxide are emitted into the atmosphere each year, which equals approximately one-half of the anthropogenic sources contributing to the greenhouse effect. It is also estimated that in the United States, 33% of the carbon dioxide emissions can be attributed to burning of fossil fuels by electric utilities, 31% by transportation activity, 24% by industry, and 12% by residential use. An American car driven 10,000 miles will release a quantity of CO_2 approximately equal to its own weight, one to two tons. Relative contribution of CO_2 by industrialised countries include 26% by the United States of America, 21% by the commonwealth of republics that once made up the Soviet Union, 17% by the countries of western Europe, and 11% by China. Some estimates suggest that that enough greenhouse gas has been emitted in the last 100 years to cause a two to five degree increase in mean global surface air temperature within a few decades (World Resources Institute, 1989).

Ecological and social effects of climate change

It is difficult to estimate the magnitude of impacts of global climate change on ecological systems and human societies. Knowledge about how these various systems function and how they interrelate is insufficient to make broad brush judgments on a global scale. This is unfortunate, considering the urgent need is to obtain a reasonable estimate of the magnitude of the impacts resulting from this phenomenon. If there were more certainty about the potential severity of the adverse effects from climate change, the social determination to deal effectively with global climate change would in all probability increase considerably.

There is a myriad of complicating factors that hinders such analyses. For instance, the world population is expected to triple before reaching a plateau in the next century (Keyfitz, 1991). How this tremendous growth in population and its utilisation of resources and expulsion of waste into the atmosphere will affect global climate change is next to impossible to estimate. One can only speculate that global change will accelerate. As developing countries become more industrialised, one can assume that the rate of discharge of air pollutants into the atmosphere will increase at a faster rate than population growth. The implications of changes in land use resulting in loss of the natural habitat necessary for the survival of the currently described 1.4 million species of the estimated four to five million organisms with which we share the planet are not known. An extensive loss of species is predicted, even without the exacerbating influence of global climate change (Soule, 1991). In addition, the ecosystem processes characteristic of the 103 global ecoregions, as defined by Bailey (1989), have not been well described, let alone assessed in terms of how the biota they represent might respond to varying climate patterns.

Changes in temperature affect rainfall, snowfall, and soil moisture (Mitchell 1990), creating stress on ecosystems (Houghton&Woodwell, 1989; Graham & Grimm, 1990; Overpeck *et al.*, 1990). Climate is the most important factor influencing the relationships between soil, vegetation, and site properties. Climate, as a source of energy and moisture, acts as the primary control for ecosystems (Bailey, 1990). An increase in global temperature will lead to sea level rise; an increase in weather extremes such as hurricanes, tornadoes, floods, droughts, heavy snowfall and accompanying avalanches; variability in frost-free days; temporal distribution of moisture accumulation seasonally; and the distribution of temperature extremes throughout the course of the year (Pine, 1981).

The response to temperature rise is also complicated by an accompanying biotic response to increased carbon dioxide which is anticipated to accompany global climate warming. In various studies, vascular plant responses due to carbon dioxide enrichment were measured and found to vary by species. These included changes in photosynthesis; respiration; water use efficiency; reproduction; growth rate; crown and nutritional qualities of grasses; and in ratios of root to shoot growth, and of seed production to vegetation growth (Strain & Cure, 1985).

Efforts to model the effects of global climate change on forested regions (Pastor & Post, 1986) have resulted in predictions of dramatic shifts in distribution of selected species (Brubaker, 1986; Graham & Grimm, 1990; Peters & Darling, 1985; Strain & Cure, 1985). Today's assemblages of organisms are likely to change owing to changing climate conditions (Davis, 1983). Those species on the edge of ranges, geographically localised, genetically impoverished, poor dispersers, slow producers, localised and annuals, highly specialised, and migratory are particularly vulnerable (McNeely, 1990). The ability of plants to adapt to new habitat in response to climate change may be hindered by constraints associated with soil conditions. In temperate mountain ranges, soils have short evolution, so that even as seeds reach areas suitable for their climate requirements, the soil conditions may not be appropriate and therefore may not be an adequate refugia from climate change (Retzer, 1974). Insects have a shorter generation time than their host plants and therefore can adapt more quickly to climate change. As a result, there will be more pressure on their hosts with the advent of climate change (Bale, 1991). Pests and pathogens of all types are expected to increase. It is frequently very difficult to establish whether ecosystems are in relative equilibrium or not. If they are not in equilibrium, then the influence of global change is more difficult to interpret. Disturbances can have a much greater influence on species associations than gradual evolution of ecosystems (Pine, 1981). All of these factors and many others associated with the complexity of the functioning of ecosystems make it difficult to predict the effects on plants of global climate change.

Yet another major complicating factor is that the general circulation models that are used to estimate global warming are not sufficiently precise to provide assessments of climate change on a regional scale (Katz, 1988). There is inadequate information to describe the global climate effects on a regional scale, particularly within the context of mountainous regions (Cisbach, 1990). It is unclear how global climate warming would affect patterns of rainfall, snowfall, and soil moisture (Mitchell, 1990).

Mountain protected areas: appropriate landscapes for early detection of the ecological effects of climate change

Mountain protected areas (MPAs) are relatively undisturbed landscapes in regions where they are located. The diverse relief of mountainous landscapes provide dramatic temporal and spatial variability (Barry, 1981). Complex landscapes provide gradients of temperature and moisture that are functions of slope, aspect, and elevation. Ecosystems associated with these diverse land forms occur in very complex patterns (Rowe, 1984; 1991). Preferred habitat may occur in mountain peaks in a great deal of isolation, which makes it difficult for some species to locate refugia (Graham, 1972; Davis, 1989). On the other hand, the range in elevation provides an invaluable and convenient mechanism to allow migration as the climate changes. Appropriate land form characteristics may include glacial substrate, surface slope, slope length, and aspect (Peterson & Woodward, 1991). The climate of mountainous areas is relatively complex, particularly when compared to neighboring areas (Barry, 1990), and invariably, there is a lack of adequate climatic data to characterise the different mountain environments (Folland, 1990). These complicated landscapes tend to be rich in biological diversity with many isolated plant and animal communities on mountain peaks, populations of rare and endangered species, and ecotones of transition between mesic and xeric vegetation assemblages.

The dynamics of subalpine pine forests, for instance, are complex. Temperature, precipitation, and storm frequency all affect their growth and productivity and any changes could alter the location of the subalpine, alpine, and other mountain ecotones (Canaday & Fonda, 1974; Pine, 1976). The timing, quantity, and distribution of precipitation (primarily snowfall) are particularly important at high elevations (Peterson & Woodward, 1991). The altitudinal tree line is a good place to detect the potential effects of global climate change (Tranquillini, 1979; Wells, 1983; LaMarche *et al.*, 1984, Graumlich & Brubaker, 1986; Graumlich, 1991; Peterson & Woodward, 1991).

The social importance of MPAs also provides a compelling reason for the the early detection of the effects of climate change. Indigenous people living in mountain areas and relying on subsistence agriculture and woodgathering are vulnerable to climate change. They tolerate extreme weather conditions and marginal growing seasons in order to sustain their independent lifestyle. Their daily lives tend to be closely linked socially and spiritually with the landscape that provides the basic sustenance of life. Although such people tend to be very resourceful in combating extreme climatic conditions, long-term changes in climate could affect the delicate balance they have established with nature in order to maintain their present lifestyle. Changes in the availability of woody plants, grasslands, and water supplies due to climate change could either improve or reduce their capacity to maintain this lifestyle.

Human consumption of resources associated with MPAs are of critical importance in the context of the impacts of global climate change. Some local peoples rely on mountain ranges seasonally for summer grazing of livestock or for hunting and trapping. New grazing patterns may become necessary due to changes in the vegetation of high elevation meadows and the availability of water supplies. The headwaters of watersheds provide important sources of water which, in some environments, could become much more restricted with the onset of global climate change. The quality of water from these MPAs might also change as a result of climate change, limiting the ability of such resources to sustain populations over the long-term in many parts of the world.

Recreation and tourism is one of the fastest growing industries in the world, and MPAs attract people interested in viewing the magnificent scenery which is often such a contrast to their urban landscapes. Sightseeing, hiking, camping, fishing and downhill skiing are typical recreation activities in MPAs. Many parks have become so popular that it has become necessary to develop mechanisms to establish social and natural resource carrying capacities in order that the resources do not become overtaxed by people. As the world population continues to grow, the demand for visiting a natural landscape in a mountain setting will also rise. It is anticipated that the growth in popular interest in MPAs for recreation will increase faster than in many other landscapes.

The metaphysical or spiritual value of mountains will always be a real and important social value which can be used to help capture people's imaginations concerning the devasting nature and extent of potential impacts of global climate change. Therefore, MPAs can be used not only to detect the adverse effects of global climate change, but also as an effective focal point for demonstrating the severity of the problem to the world.

One further important value of MPAs is that they are centres of rich biological diversity which has social as well as biological significance since many people believe that all species have a right to survive and prosper on this planet. A system of ecological preserves are considered by such people an ethical necessity for a society that calls itself civilised.

Mountain protected areas: the potential for a global network for monitoring the effects of climate change

MPAs could become the centerpiece of a global monitoring network to detect global climate change. Such as system is needed but not yet in place. Noone has even adequately addressed, in a theoretical sense, the topic of monitoring ecosystems in the context of global environmental monitoring programs (Bailey, 1990). Several national and international organisations and agencies have expressed interest in establishing worldwide monitoring networks for assessing the effects of possible climate change. Most notable are the National Air and Space Administration's Earth Systems Programme, the International Geological Union's Commission on Geographical Monitoring and Forecasting, the International Geosphere/Biosphere Programme; the Environmental Monitoring and Assessment Programme (EMAP) of the U.S. Environmental Protection Agency, the Global Environmental Monitoring System (GEMS) of the United Nations Environment Programme, and the U.S. Global Change Research Programme.

Table 1.
Mountain Protected Areas (MPAs) by Biogeographical Realm
(From: Thorsell & Harrison, 1991)

Biogeographical Realm	Number	Total Area (ha)
Indomalaya	53	8,811,898
Afrotropical	35	10,986,512
Palaeartic	146	30,120,611
Nearctic	93	153,707,666
Neotropical	82	30,393,615
Oceania	8	3,598,032
Australia	4	1,840,459
Antarctic	11	2,086,861
Total	432	240,544,654

A total of 432 MPAs (Categories I-IV) with a minimum size of 10,000 hectares and a minimum relief of 1,500 meters have been identified that fall within the World Conservation Union's hierarchy of designated protected areas. This constitutes 42% of the total global area devoted to nature conservation, or 24% of the system if Greenland National Park is excluded from the total (Thorsell, 1991). These MPAs are representive of the biogeographic realms defined by Udvardi (1975). Table 1 lists the number and total of MPAs by geographic realm distributed throughout the world (Thorsell, 1991).

An initiative is just underway to establish a database on these IUCN designated MPAs (Peine *et al.,* 1991). Once this database is assembled, it would be possible to determine the relative importance of these various protected areas as strategic components of a global monitoring network. The first level of analysis is to characterise the latitude range, elevational gradient, and continental position of the areas. At the global scale, this is how ecosystem patterns are controlled (Bailey, 1990). Secondly, the MPAs can be described in the context of their ecoregions as defined by Bailey (1981). A third step would be to describe the distribution of generalised land form categories that are present within the MPAs and surrounding landscape. The land use patterns would be described in general terms (Parker, 1992; Peterson & Woodward, 1991). Suggested landform characteristics include geological substrate, surface shape, slope length, and aspect (Hammer, 1991). Fourthly, a generalised species area analysis could be conducted to indicate whether the size and configuration is adequate to protect the biodiversity on the landscape, particularly for populations of large mammals (Newmark, 1985). A fifth step in defining a network of monitoring sites within the MPAs is to look for those sites that have similar characteristics across a global system. Such characteristics might include a particular range of elevational gradient; a similarity in slope and aspect as they relate to latitude; the orientation of a waterbasin with respect to prevailing wind patterns; and selection of particularly sensitive areas within the waterbasins and along a system of line transects where sensitivity to climate change is greatest. Such sensitive areas could include alpine and subalpine vegetation, tree line, ecotones between xeric and mesic plant communities; first and second order streams; wetlands and bogs; snowfields; glaciers; and cliff faces. The final step in the delineation of the global network would be to identify climate sensitive bioindicator species that are associated with the selected monitoring sites and to develop protocols to describe and monitor population dynamics. The development of standard protocols for monitoring meteorological, hydrological, and chemical cycling dynamics should also be established.

It is also important to match the theoretical basis of such a monitoring system with the actual capability to operate such a programme in the field. Some MPAs have long histories of research activity and are in a good position to provide access and appropriate logistic support for interested scientists. Other MPAs are almost totally undeveloped, with minimal scientific activity taking place.

A cursory analysis of steps 1 through 3 could be conducted utilising the information base to be assembled by Peine *et al.* (1991). The World Conservation Union could then take the analysis to some of the global environmental monitoring networks that are emerging and encourage that consideration be given to utilisation of MPAs within the context of those initiatives, such as UNESCO's Man and the Biosphere programme or the Global Environmental Monitoring System (GEMS) of the United Nations Environment Programme.

Mountain protected areas: case examples

Great Smoky Mountains National Park

The ancient Appalachian Mountain range in the eastern United States extends from Maine to Georgia, achieving its greatest elevation in the southeast. The topography consists of moderately sharp-crested, steep-sides ridges separated by deep V-shaped valleys. Lesser ridges form radiating spurs from a central ridge line. Many of the mountain ridges branch and subdivide, creating a complex of drainage systems with thousands of miles of fast-flowing clear mountain streams. Great Smoky Mountains National Park (GSMNP) contains 45 major watersheds and over 2,100 miles of streams. The water table tends to be near the surface in almost all regions. Pre-Cambrian metamorphic rocks consisting of gneisses, schists, and sedimentary rocks from the pre-Cambrian Ocoee series are the most common, while secondary rocks in the Appalachian Valley are the youngest. Owing to the rugged topography, the mountainous region is relatively sparsely populated.

Biological diversity at all levels (for example, genetic, species, and community levels) is high with many endemic species. The salamander fauna is rich and locally diverse. The high mountains and rich array of microclimates support this diversity, and understanding the importance of this mountain mass to regional diversity in the context of climate change is critical. The deeply dissected landscape present at the southern end of the Appalachian chain provided a refuge for a host of temperate and boreal species during the Pleistocene glacial periods.

This has resulted in a rich vegetation mosaic comprised of more than 1,500 species of flowering plants (including 130 species of trees) and over 2,200 cryptogams. Over 30% of the park's forests are high in "virgin" attributes, areas least impacted directly by people. Areas which were farmed or logged have been recovering for varying periods of time and therefore represent a wide range of successional stages. Deciduous broadleaf and evergreen coniferous forests dominate the vegetation, but treeless grass and heath balds, open wet meadows, and cliff communities occur as well. Vegetation changes continuously with elevation, slope, aspect, and topographic position.

Fourteen major forest types are currently recognised within the region. On mesic sites, low or mid-elevation cove hardwood (mixed mesophytic) and hemlock-hardwood forests grade, with increasing elevation, into northern hardwoods and finally, at about 1,500 meters, into spruce-fir. On a gradient from mesic to xeric, the cove hardwoods are replaced by mixed oak, xeric oak, and oak-pine. Heath balds represent the xeric extreme at upper elevations and are dominated by ericaceous shrubs. Perhaps most notable are the cove hardwood and the spruce-fir. Cove hardwoods may contain upward of 20 different species in the canopy at any one site. The understory is also diverse: a single 0.1 ha plot may support more than 50 species throughout the year.

The spruce-fir forest type occurs only at the highest elevations and contains the largest contiguous block of virgin red spruce *Picea rubens* on Earth. Fully 75% of all Southern Appalachian spruce-fir occurs within the boundaries of the park. Additionally, grass balds, ridges, cliffs, and landslide scars within these high elevation forests support the growth of rare regional endemics.

Fifteen plants are listed as candidates for federal protection as threatened or endangered species. Moreover, 120 species are recognised as rare enough to be of managerial concern. A similar number of bryophytes, lichens, and fungi, are also considered rare at the regional, national, or global level. The diverse fauna includes at least 50 native mammal species. This biological diversity is internationally recognised, and GSMNP was designated one of the first International Biosphere Reserves and was designated a World Heritage Site in 1984. Within the context of this complex topography and rich biological diversity, the National Park Service manages a variety of facilities and services for an unprecedented number of visitors. With over 50% of the nation's population living within a one-day drive of the park, GSMNP has the highest number of visitors of any national park in the United States of America.

Effects of global climate change which might have an impact on the ecosystems of the park include changes in the range of annual and seasonal temperatures, alterations in the quantity and timing of precipitation, lower runoff, reduced soil moisture and increased temperatures. Such changes may result in forest decline, shifts in structure/function of natural communities, overall reduction in biodiversity and nutrient availability, and increases in fire frequency and intensity, and the occurrence of exotic pests and diseases. Climate change may act alone or with other sources of stress, such as atmospheric pollution, insect infestation, or plant disease, to affect species distribution.

Specifically, the entire spruce-fir ecosystem is predicted to be in considerable jeopardy in the event of significant climatic change. Fraser fir *Abies fraseri* is endemic to the Southern Appalachians and its survival is in question owing to infestation by an exotic insect pest. In addition, most of the 95 Southern Appalachian endemic or near endemic vascular plants are found on high elevation north-facing slopes. Changes in temperature and moisture might eliminate them from the park and, in cases of endemics, might lead to extinction. The region's nonvascular plant flora, such as mosses and liverworts, are closely tied to moisture-laden environments, with individual plants existing in very specific microhabitats. In GSMNP, there are 428 species of bryophytes, of which 175 are considered rare at the global, national, and park level. Some are rare, need habitats with exacting temperature and moisture requirements, and cannot be artificially propagated.

Aquatic organisms can be sensitive to changes in flow rates and temperature regimes. The native brook trout *Salvelinus fontinalis* has been a subject of research activity for many years in the Southern Appalachian region which represents the southern extent of the species range. The distribution of the species within the region is limited by temperature and minimum flow requirements to the larger of the multitude of streams draining the region's forested mountain watersheds. The status of brook trout streams may serve as a key indicator of regional ecosystem response to climate change since the extent and condition of this habitat may be directly affected by changes in precipitation and temperature.

The region's streams might also be subject to critical changes in chemical composition as a consequence of altered patterns of elemental flux in watersheds. The streams are very low in ionic concentration and poorly buffered against climate influenced chemical change. Present day deposition of atmospheric acidity in the park exceeds that in all the other large U.S. national parks. Acidification of streams has been demonstrated and changes in climate may exacerbate this existing environmental problem. It has been observed that episodic stream water acidification occurs when accumulated acidic materials are leached from waterbasins into streams during periods of elevated runoff (Elwood, 1985). The magnitude evidently depends on the length of time over which sulphur and other atmospherically transported materials have been deposited. Data collected in GSMNP suggest that nitrification of soils can also add to the accumulation of acidity during protracted dry periods. Thus, if climatic change results in greater frequency and intensity of drought, or more extreme alternation between wet and dry conditions, periods of episodic acidification and coincident stress on aquatic organisms may be more frequent or extreme. The significance of the potential synergistic effect of climate change and atmospheric pollution is largely due to the present at-risk status of the resource.

From 1985 through 1988, a period of extreme drought occurred in the Southern Appalachian highlands. Environmental response to this climatic condition provides significant insights to the potential impacts from a dramatically changed environment. Air stagnation during summer months was extreme, resulting in significant build-up of dry particulate matter such as ammonium sulphates in the atmosphere and contributing to a serious problem of regional haze. These episodes sometimes result in an 80% reduction in visibility, usually occurring during the height of the visitor season. Research has shown that viewing mountain scenery is a primary component of the quality of visitor experience. Another dramatic impact was in the streams, where low flows and abnormally high temperatures resulted in occasional die-offs of fish, and in the loss of almost an entire age class of salmonids (because of lack of reproduction).

A general slowing in forest productivity was also observed, and the high elevation red spruce forest experienced a virtual shutdown in growth during this period. A 5-year study of crown condition during drought showed a decline in healthy crowns on red spruce trees from 85% in 1985 to 50% in 1989 (Nicholas & Zedaker, 1990). The crown condition is thought to have been exacerbated by air pollution in addition to the drought conditions. There was a dramatic increase in fires in the park during the drought; 1988 being an especially bad year, with 41 fires recorded. Although visitors to the backcountry enjoyed drier conditions for hiking, many complained of the lack of water at high elevation, where a series of springs normally provide adequate water year round.

Glacier National Park (GNP)

This park is ideally suited to the study of the effects of global climate change because of its biophysical diversity, the emphasis by park managers on ecosystem-level research and monitoring, and the organisational commitment to fostering excellence in science. The diversity has resulted from GNP's unique geographic position and elevational zonation. Five floristic provinces and three major watersheds converge in an area influenced by both maritime and continental climates. The park is located in the northern Rocky Mountains at the southern edge of arctic-boreal influences, while Pacific and Great Plains environments reach their eastern and western limits in the park. Quaternary glaciation has isolated many populations, and steep topography imposes discrete elevational zonation on climate-regulated communities. These biophysical traits heighten sensitivity to climate change and increase the opportunities for climate-related hypothesis testing and monitoring. Many species exist at the margins of their ranges, ecotones are sharply delineated, and climate-restricted settings, such as the alpine zone, are common. Even slight climatic shifts should rapidly exceed environmental tolerances, resulting in measurable change across diverse parameters, such as species variability, life zone distribution, glacial movement, net respiration, and hydrologic balance.

GNP's science programme emphasises ecosystem-level integration of information including that from Waterton Lakes National Park and the nearby Bob Marshall Wilderness Area and Banff National Park. Over this landscape, studies of species, communities, and hydrology can be assembled within entire small watersheds to model response patterns across elevation gradients, including changes in ecotones, primary productivity, and nutrient transport. Climate parameters, measured across the same gradients, can detect trends to establish rates of change when correlated over all responses. Ecosystem-level models of climate change and biophysical response can then be developed to assess net system-wide effects and project potential climate scenarios into future landscapes.

Existing organisational support offers an efficient and required means to initiate and sustain the proposed research. GNP's science programme includes expertise in aquatic and terrestrial ecology, geography, statistics, and computer processing. A geographic information system is operational, ecological inventory and monitoring is in progress, and physical facilities are available on site. A high level of interest exists among managers and scientists from Parks Canada and the University of Montana. Links to many institutions are firmly established, broadening accessible expertise and support. A large and rapidly accumulating base of information is already available to serve as a foundation for further research. The combination of broad-based experience, information, and operational support presents a substantial opportunity for climate change research.

Mountain protected areas: management initiatives

Natural resource sensitivity analysis

The first step an MPA manager should take in conducting a natural resource sensitivity analysis is to assemble relevant information on the area and convene a panel of experts to identify potentially vulnerable natural resources of the MPA. This should be based on information assembled for the MPA and on the experts' firsthand knowledge of the area. The goal of this exercise would be to define a scenario of probable sensitivity due to significant long-term change in climate. It is not necessary to conduct this analysis in the framework of any particular climate scenario, such as warmer temperatures, drier conditions, and more extreme storm events. What is important is to identify resources that are particularly dependent upon or sensitive to the dynamics of climate.

A good place to start is to characterise the prevailing weather patterns. Most mountain ranges tend to experience much wetter conditions on the windward than the leeward side and this provides a basic influence on the regional distribution pattern of mesic and xeric habitats which support species with very different tolerances to climate change.

Water resources are a key factor and natural lakes provide a cumulative indicator of the hydrologic impacts of climate change over the waterbasins supplying them. Lake volume, height, and chemistry are valuable indicators of climate influences. Wetlands and bogs support species that are moisture dependent or tolerant. The edges of these systems are a good place to observe early responses to climate change. Alpine and sub alpine vegetation should be examined as obvious places to detect the effects of climate change and ecotones between vegetation types are vulnerable areas that may support sensitive species. The transition zone between coniferous and deciduous temperate forests is an example. MPAs may also be the first places where changes in species distribution is detected as climate changes.

Wildlife sensitivity to climate change may be reflected by shifts in habitats. Small mammals may be useful indicators as they are more easily sampled than larger mammals and can be very sensitive to soil temperature and moisture gradients.

The identification of sensitive ecosystems and species should be conducted against the background of other changes such as major disturbances which might affect the response of species to climate change. Many MPAs are already subject to a very high degree of disturbance from fires, agriculture, logging, and human settlement. These areas will have different species composition and distribution and therefore may react differently to relatively undisturbed natural areas.

Rare and endangered species are important considerations in the context of sensitivity analysis to global climate change. Their range is often limited or disjunct and hence they may be more vulnerable to climate change as a consequence of isolation of populations. Their restricted gene pools could restrict their capacity to adapt to subtle habitat changes. At the other end of the spectrum, alien species should also be monitored in case they extend their range into the protected areas under changed climatic conditions.

Once the dynamics of moisture and temperature gradients reflecting slope aspect and elevation are defined and the sensitive ecosystems, such as alpine and subalpine meadows, tree lines, and ecotones between plant communities, have been identified; then potential bioindicators vulnerable to climate change can be chosen.

On completion of the analysis, the experts should have identified areas in the MPA that would be appropriate for monitoring the effects of global climate change; and compiled a list of climate change bioindicator species that merit further study and analysis.

In GSMNP, sensitive areas include the high elevation spruce-fir forest ecosystem, ecotones between xeric and mexic forests, rare plant communities on high elevation cliff faces, and high elevation streams. In GNP, the glaciers, alpine meadows and wetlands would be particularly sensitive to climate change.

Human resource sensitivity analysis

On many of the boundaries of the designated MPAs around the world, there reside indigenous populations of people who have lived off the natural resources of these mountain environments for countless generations. The cultures of these people demonstrate mechanisms by which man and nature can coexist on a marginal yet operable scale of time tested dimensions. The lessons that can be learned from indigenous populations living in mountain environments are quite significant. These people have learned how to live on what nature offers. Additionally, they hold a wealth of information concerning ethnobiology or how man can use native plants and animals to serve his needs. The pharmaceutical industry is funding research all over the world to use information from what Anglo-Saxons would call "witch doctors and medicine men," people who administer medicinal herbs and spices, for health and spiritual reasons, to indigenous populations. The rituals performed and the utilisation of plant and animal materials provide a synthesis of generations of discovery of the value of native materials to man. Therefore, it is important and instructive for managers to document how indigenous populations use the natural resources of MPAs.

This information can then be a cross-referenced with the natural resources sensitivity analysis described above to identify potential conflicts that might occur with the advent of global climate change, either due to changing availability of water or loss of species or ecosystems on which the native people depend. Seasonal grazing in high country that requires access to a traditional water supply may be threatened and alternative seasonal grazing lands may need to be established to reduce impacts on the agricultural activities of indigent people.

This concern is not limited to populations living within or adjacent to MPAs since a reduction in water supply dependent upon an MPA waterbasin could cause significant regional hardship. Recreation and tourism could be adversely impacted, since degraded ecosystems or loss of high profile species could reduce the attraction of the area to visitors.

GSMNP is the most frequently visited national park in the country. If climate change results in more air stagnation, then the resulting higher levels of air pollution will reduce visibility. The scenic views are the most popular recreational attraction in the park (Peine & Renfro, 1988). If the climate becomes drier and warmer, there will be problems with water supply in the higher elevations of the backcountry (Renfro *et al.,* 1991). Recreational fishing would be adversely affected (Moore, pers. comm., 1991), as would other water-based activities, such as "tubing" and swimming. If climate change results in an increase in forest fires, insect infestation, and pathogens, the visual appeal of the park could be greatly diminished. The most important aspect of the park for visitors is a healthy environment and the perception of a pristine environment that is being protected in perpetuity is an extremely important social value (Peine & Renfro, 1988).

Regional landscape analysis

In addition to the sensitivity analysis, managers of MPAs should conduct regional landscape assessments to evaluate how the MPA relates to the distribution of natural resources on a regional scale. As the human population centres surrounding MPAs continue to expand and natural landscapes are converted from native habitat to manipulated environments, populations of native plants and animals become fragmented and reduced in size. This creates an isolated patchwork of natural areas in which many species will no longer have adequate habitat area to ensure survival. The MPAs become islands of natural habitat surrounded by manipulated environments which form barriers to migration for species residing within the reserves. Conflicts abound all over the world as a consequence of ungulates and carnivores ranging outside protected areas during seasonal movement in search of forage and water or to breed. New projects are frequently proposed in the vicinity of GNP, and at GSMNP, the tourism industry is expanding rapidly, creating an urban barrier surrounding many portions of the park, particularly on the Tennessee side. Conflicts frequently occur when black bear *Ursus americana* seeking food range into communities adjacent to the park. Any long-term assessment of the effects of climate change must include an analysis of the context of land use conversion on a regional scale to truly appreciate the impacts on biological diversity.

To assess the regional context where the MPA is located, a large scale map should be prepared which portrays at least the following: designated protected areas; areas dedicated to renewable resource management, such as forestry and range land; non-renewable resource extractions, such as the mining of minerals; population centres; major point sources of pollution; and any landscape level disturbance that might be relevant, such as large scale fire, flooding, insect infestations, or the range of invasions by alien plants and animals.

Existing and potential movement corridors for native plants and animals should be identified for ridge lines and waterways. A species area analysis should be conducted at the regional scale to identify the adequacy of the protected habitats for wide-ranging species such as ungulates and carnivores that consistently travel beyond the boundaries of the MPAs. Areas of human conflict with these species, such as illegal hunting, agricultural activity and residential development should be identified on the map as well.

Another important exercise is to delineate projected future regional land use patterns for activities such as agriculture, forestry, and mining. The future should generally be defined in one or two 25-year intervals. Major transportation corridors can be used to project future commercial, industrial, and residential growth of human populations. The development of a plan for the future is critical in evaluating the available options that managers for sustaining biological diversity within MPAs during periods of significant climate change.

In the case of GSMNP, the urbanisation of private lands adjacent to the boundary of the park is anticipated to continue unabated well into the next century until the entire border of the park is virtually lined with tourism-related development. This phenomenon will occur first in tourism-based communities on the Tennessee side of the park. On the North Carolina side, it is anticipated that a less intensive level of commercial development will ring the park as well, although it is less likely to be situated directly on the borderline of the park. The national forests that are adjacent to the Smokies on the northeastern and southwestern borders provide the greatest potential for species movement. Interstate 40 is a four-lane highway that divides the Southern Appalachian mountain range. There are two tunnels and several culverts under the road which are actively being utilised by wildlife for movement. The publicly owned land in these migration corridors has not been managed with this land use perspective in mind. There is a need to develop a land use plan for these migration corridors that is consistent with the needs of wildlife.

In GNP, there is extreme potential for encroachment from adjacent lands with activities including a major strip mine operation, clear cut forest harvest practices, and community development. These conditions are particularly important at GNP due to the range requirements of various wildlife species.

Conceptual framework for monitoring

A critical step toward developing a global climate change program for managers of MPAs is to design a conceptual framework for a monitoring program that is oriented toward identifying early signs of global climate change and the biological, geophysical, and chemical responses to that change. A team of experts familiar with the resources of the MPA can be brought in to design such a program in a short period of time. In many cases there has been a long history of research already ongoing at the MPA which can be applied during the design of such a programme. The monitoring programme should be devised at different scales of resolution, including landscape, research watersheds, community, and species levels.

At the landscape level, an important first step is to establish a map of the MPA with a geographic information system. Appropriate themes for the map database that could be accumulated over time include the topographic features, vegetation patterns, water resources, human development, and disturbance history. It is cost effective to archive satellite imagery for the area over time if possible. Such information can be used to detect broad scale changes in vegetation patterns, snowfields, rock slides, human development, and so forth.

The heart of the conceptual monitoring programme should be a series of paired research waterbasins designed to represent typical landscape patterns in the MPA oriented to the windward and leeward sides of the prevailing weather patterns.

Some minimal monitoring activity should be maintained via staff working in the MPA. By tracking a few key parameters systematically for the long term, scientists will be attracted to the area for further study. Typical kinds of basic monitoring information that would be appropriate at the waterbasin level includes flow rates, temperature, and chemistry for first or second order streams; meteorology, such as wet deposition, temperature, and humidity; glacier and snow field depth and position; and maps of vegetation distribution on the waterbasin. The research waterbasins should be chosen in part because they represent areas considered to be sensitive to climate change as described in the previously mentioned sensitivity analysis.

The community level component of the monitoring strategy is to establish study sites at selected sensitive areas within the research waterbasins. Vegetation plots, small mammal plots, and so forth, should be established to document population dynamics for vulnerable ecosystems. First, second, and third order stream segments should be established and populations of macroinvertebrates and fish described. The Smithsonian Institute has established a system of nested plots which can be utilised to document various biological realms in the study of biodiversity. One plot, for instance, could be dedicated to soil analysis while others are dedicated to small mammals, amphibians, insects, herbaceous vascular plants, and woody plants. By choosing a homogeneous site for this series of plots, the relationship among the various data elements can be readily compared. It is very important to document the location of these study plots and to manage these intensive study sites carefully because the sampling can be very destructive if not carefully supervised. Conscientious data management and archiving are also extremely important.

The community level work can also be described within a broader basin context by establishing transects across topographical features, such as elevation gradients, soil temperature, and moisture gradients. Along these transects, point counts of a subset of the information collected on the study plots can be recorded to provide a means for direct comparison.

Species populations identified from the sensitivity analysis should be described so that their dynamics can be monitored over time. Factors which should be considered in establishing a monitoring programme at the species level include presence and absence, distribution, abundance, production, mortality, and phenology.

The GSMNP is one of four national parks in the U.S. to develop a prototype natural resources monitoring programme. That effort is useful for the study of climate change GNP was selected to one of ten U.S. national parks targeted for the study of the effects of climate change.

Strategic plan for species conservation

The sensitivity analysis should provide MPA managers with reasonable insight into which species are at the greatest risk given the potential climate change. Under some of the worst case scenarios that have been propounded, there may be such dramatic adverse impacts on ecosystems that it would be impractical to focus on traditional single species management. The Endangered Species Act of the United States, which is focused on single species, is controversial and there is considerable political pressure to rescind it because of the social conflicts associated with protecting single species. Ideally, environmental interests should focus on ecosystem level conservation. Protected areas should be of a size and configuration sufficient to sustain a large percentage of the plant and animal communities occuring naturally in the ecosystem targeted for protection. Nevertheless, there will always be an interest in preserving individual threatened species. The advent of climate change over the long-term will make the job of single species protection daunting.

An important consideration when evaluating the viability of an endangered species population and its vulnerability to climate change, is the critical population size and distribution necessary to guarantee survival. Determining the role that genetic variability contributes to the viability of the population is also important. Habitat characteristics relevant to climate should be characterised, such as soil moisture and temperature relationships, average number of frost-free days during growing season, temporal distribution of precipitation, slope and aspect affecting orientation to the sun, dependency on water supply, and so forth. The relationship of these climate-related factors to the life history of the species is also important. How, for instance, might climate change affect propagation? Invariably, such an exercise will generate more questions than answers. The greatest value in going through such a process is in defining the research and monitoring needs for the species concerned. This process is also useful in determining whether there is a need to establish a new population of the species at another location. Habitat manipulation to protect species is becoming a more accepted practice in MPAs. For some plant species, it may be appropriate to store seeds or establish a seed bank.

In GSMNP, the native brook trout presents a good example of a species vulnerable to climate change. There is a southern strain of this species that has recently been identified as being genetically distinct (McCracken *et al*, 1991). This southern strain is isolated, with only four populations in the park occuring in second and third order streams. The majority the 2,000+ miles of streams in the 28 waterbasins in the park are populated in their upper reaches with brook trout introduced in the park from hatchery fish reared in Northern Appalachian waters which represented a different genome. The challenge is to provide an adequate population of the southern strain of native brook trout on several more streams and to extend their range into lower elevation streams to reduce their vulnerability to climate change.

Strategic plan for cultural resources

Based on the cultural resources sensitivity analysis, plans should be made to gradually change patterns of social behavior that may be at risk through climate change. Conducting research to develop drought resistent crops; identifying alternative sources of energy for domestic consumption such as solar or hydrologic devises to substitute for firewood; and, locating alternative land for the grazing of domestic stock are examples of potential activity to include in such a plan. No such activity is necessary for GSMNP or GNP since neither area has indigenous people living within the boundaries.

Conclusion

There are several steps which land managers should take to prepare for what could be a cataclysmic change to the natural resources in MPAs within the next 50 to 100 years. Preparing now for such a vaguely defined process requires a great deal of courage and vision. Most land managers are desperately trying to respond to daily crises in the operation of their parks without having the luxury to plan far into the future. Land managers have difficulty planning 6 months in advance, let alone adhering to annual and 5-year plans. What is suggested here is that land managers take the leadership in showing vision in 20-, 40-, and even 100-year planning horizons. Such a perspective has not been considered necessary by managers of protected areas in the past, but with the advent of global climate change, now is the critical time to take action. Ignoring potential climate change now may result in losing the option to deal effectively with it. Some scientists predict that if no action is taken now, within 50 years the greenhouse effect may become unmanagable, no matter what adjustments are made by societies to suppress emissions of greenhouse gases.

Never has society been faced with such a daunting challenge that requires a faith in science, a commitment to focused public opinion, and an action plan that begins the process of controlling greenhouse gas emissions. The industrialised world is supposedly well-informed and therefore there should be a greater chance of establishing the political resolve to take the steps necessary to control these emissions in such countries. Managers of MPAs can play a critical role in this process by providing the equivalent of the traditional role of the canary in the coal mines. Coal miners used to take canaries underground to evaluate air quality and they knew that if the canary died it was time to get out of the mine. If the organisms in MPAs show signs of stress due to climate change and these phenomena are systematically documented around the world, then the alarm and concern may be raised through effective communications with the industrialised world. Managers of MPAs share a great responsibility and opportunity to provide leadership on this critical issue

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Impact of climatic change on tropical forests in Africa: implications for protected area planning and management

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Summary

The current distribution of forests and protected forest areas in tropical Africa is discussed. Climate is thought to be the main factor determining the distribution of vegetation types in Africa, with the direct and indirect affects of human activity becoming increasingly important during recent times. Evidence is provided for temporal variations in climates and changes in the extent and composition of forests in tropical Africa, particularly during and since the last major world glacial period, ca. 70000 BP to ca. 10000 BP.

Meteorological and anecdotal evidence indicates warming and drying of climates in tropical Africa has taken place over the last 30 years. These changes may represent the early stages of global 'greenhouse' warming, in addition to being a possible consequence of local environmental degradation. Climate models predict a continued warming during the next 100 years or so but changes in effective precipitation have proved more difficult to predict, largely because of the complexity of the temperature/water availability balance; all predictions are hampered by a shortage of meteorological data.

Some changes in the distribution and composition of plant communities are expected, although uncertainties over future climates present difficulties in predicting their precise response. The mutability of species and vegetation types in tropical Africa has implications for future research and the location and management of protected forest areas. These are:

1) the need for further research into the ecological requirements of forest taxa and into the impact of future climatic change on forests;

2) the key importance of protected areas in those relatively climatically stable parts of tropical Africa;

3) the need for protected areas to span substantial climatic (temperature/rainfall) gradients and be linked by corridors of natural/semi-natural habitat; and

4) the need for greater human intervention, particularly in the *ex situ* propagation and assisted dispersal of threatened species.

1. Introduction

There is evidence to suggest that tropical Africa is currently experiencing rapid changes in climate, at least a part of which appeals to be human induced. Continuation of these changes could undermine the conservation of Africa's forests by altering their distribution and composition, as forest conservation strategies have largely been developed under the assumption of stable climatic conditions. This paper discusses the implications of predicted future changes in climate for research and for the location and management of tropical Africa's protected forest areas.

In order to ensure the long-term survival of forests, conservation strategies presently being formulated will need to take into consideration the likely nature and rate of future environmental change. There are, however, a number of problems that first need to be addressed, namely:

1) determining the main environmental controls on the distribution of forests at present;
2) predicting how and at what rate these controls will change in the foreseeable future; and
3) estimating the response of forests to these predicted changes.

These problems are, to some extent; solvable: the first by recourse to the present environment, the second and third through studies of the history of environmental change and the use of predictive models.

2. The distribution of forests in tropical Africa

Figure 1, based upon the vegetation maps of White (1983), illustrates the present extent of forests and transitional forests/derived grassland in tropical Africa. From Figure 1 it can be seen that lowland rain forest forms a broad equatorial belt in Africa, within which there are two major gaps. The largest of these stretches from eastern central Africa to the Indian Ocean and the coastal forests of Kenya and Tanzania. The second, otherwise known as the 'Dahomey Gap', is less extensive and is located in West Africa in Togo and Benin.

Tropical African forest is commonly divided into lowland and montane types (Figure 2). The altitudinal location of the boundary between the two varies according to definitions of the types and location. In central Africa lowland forest is often considered to grade into montane forest over the altitudinal range 1,500 m to 2,000 m. Montane forests are more restricted in area than lowland forests, owing to the limited occurrence of highland, are usually not so tall, and have fewer plant strata.

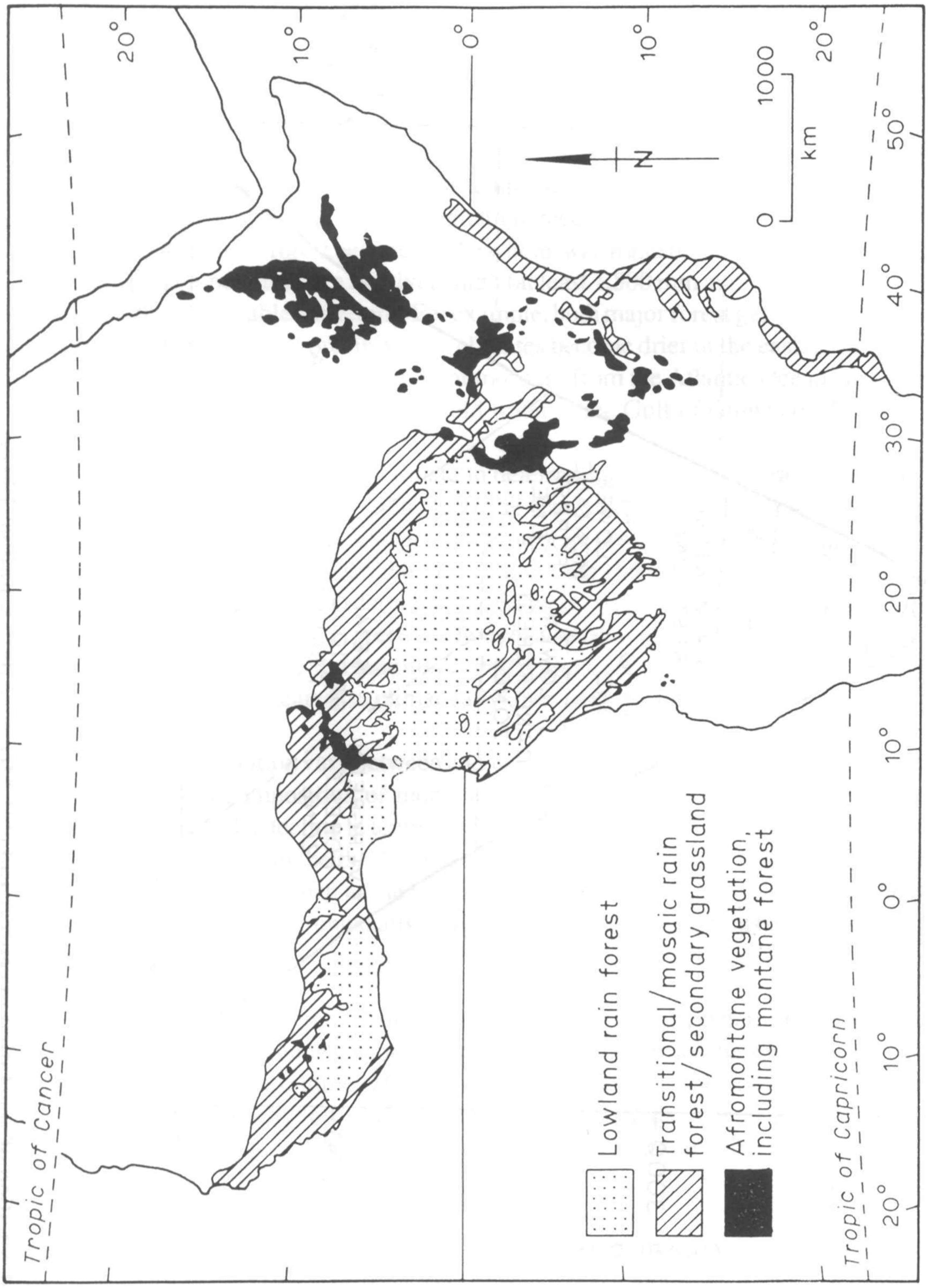

Figure 1.
Present extent of forested area in tropical Africa. (After White, 1983)

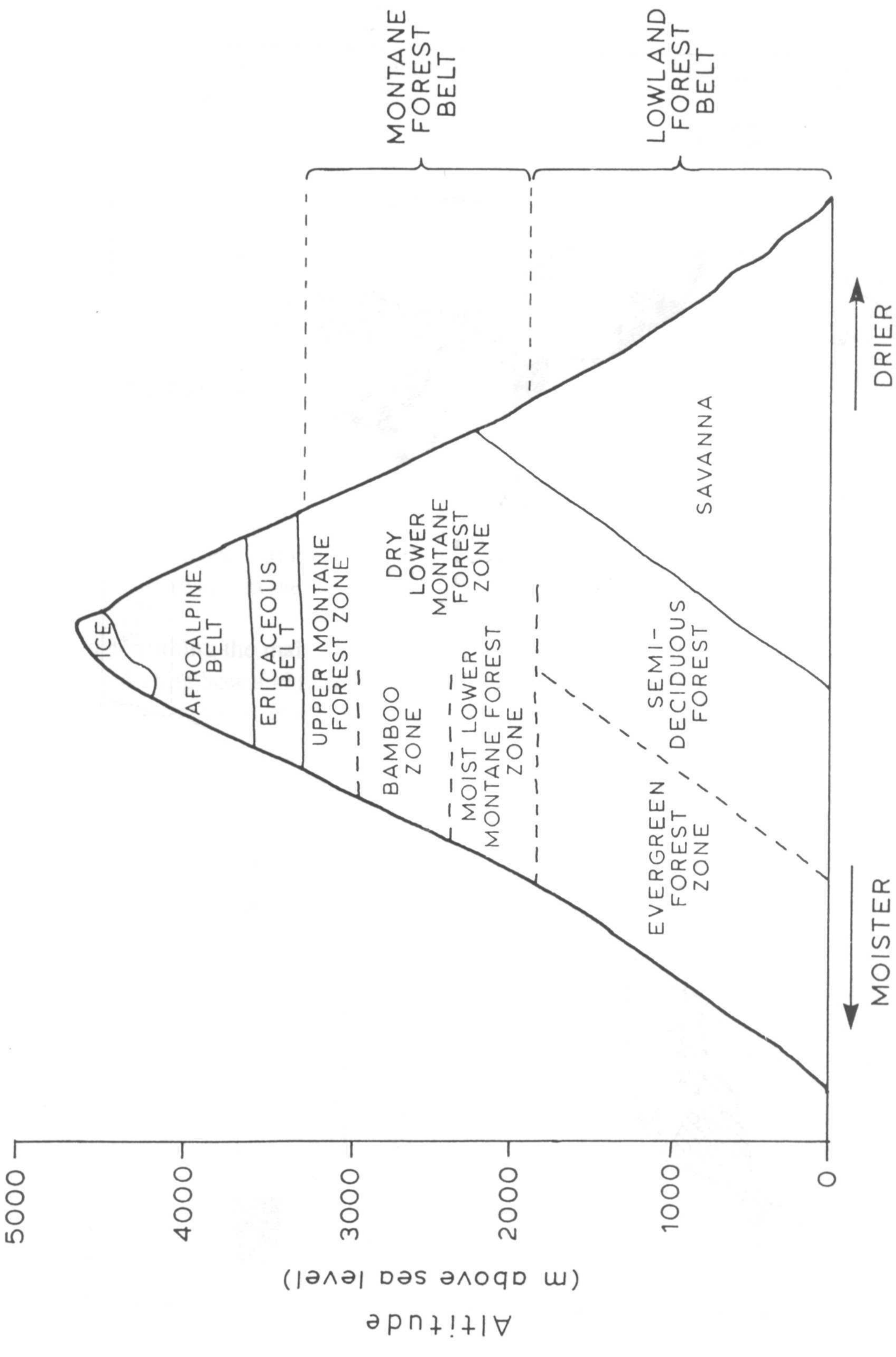

Figure 2.
Altitudinal zonation of vegetation in central and east Africa. (After Hamilton, 1989a)

Forests in tropical Africa have a similar physiognomy to forests in Central and South America and Southeast Asia. However, forests in tropical Africa differ in terms of their species composition and overall lower diversity (Richards, 1973; Thorne, 1973), indicating that they have evolved in virtual isolation.

2.1 Factors controlling forest distribution in Africa

On a continental scale, the natural distribution of forests in Africa is predominantly controlled by climate, in particular by levels of temperature and effective precipitation (the difference between the total amount of precipitation received and the amount lost to evaporation). Climates within the forest belt are, on the whole, warm and moist. Annual levels of precipitation and mean temperatures are relatively high (at least 1,500 mm and 18°C respectively), although there are considerable variations. For example, both major forest gaps are associated with lower than expected levels of precipitation: climates become drier in the eastern part of the continent because of the declining penetration of moist air from the Atlantic Ocean, and in the Dahomey Gap as a result of the upwelling of cold water in the Gulf of Guinea off West Africa.

The important role played by climate in determining the potential ranges of species has long been appreciated (von Humboldt, 1807; de Candolle, 1855). More recently, Hall & Swaine (1976; 1981) identified the total precipitation received during the wet season as the single most important environmental variable determining the floristic composition of forests in Ghana. Climate also affects physiognomy. For example, within lowland forest the great majority of understorey trees are evergreen, although a substantial proportion of the taller trees are deciduous. According to Hamilton (1989a) and Lebrun & Gilbert (1954) the proportion of deciduous trees is greatest in climatically drier areas.

Levels of precipitation vary between and within highland areas, and these differences influence the nature and composition of montane forests. Temperature is also an important factor in highland areas; the decline in temperature with altitude is marked by a characteristic altitudinal zonation of vegetation belts. The influence of temperature on vegetation is best illustrated in those highland areas, such as the Usambara mountains in Tanzania, in which the temperature/altitudinal gradients are unusually steep. In such cases, vegetation belts descend to abnormally low altitudes.

Although the potential ranges of species are often physically determined, their actual distribution may be a consequence of biological factors, such as the efficiency of dispersal and competition. For example, *Hagenia abyssinica*, a montane forest tree in tropical Africa, descends to unusually low altitudes in south west Uganda in areas of abandoned or marginal agricultural land, possibly because of the absence of natural competitors.

3. The distribution of protected forest areas in tropical Africa

Active measures to conserve forests in tropical Africa are based largely upon a network of forest reserves and national parks. The distribution of national parks has recently been mapped by the World Conservation Monitoring Centre in Cambridge, UK (Figure 3). Similar information on forest reserves is presently being compiled, but is unfortunately not yet available (Donald Gordon, pers. comm.).

Many forest reserves were established during the colonial period in Africa, largely to ensure the supply of commercial timber (although the importance of a substantial forest cover was realised at a relatively early date in some countries such as Uganda). National parks in forest areas, where the main emphasis is on conservation and not exploitation, have a much more recent origin. For example, Bwindi-Mgahinga and Ruwenzori national parks were designated by the Ugandan government in August 1991. As a result, the number of national parks established in forested areas to date is low and their combined area, small. Individual park areas are also, in general, relatively small when compared to national parks in other vegetation types, such as dry savanna and miombo woodland. Furthermore the network of national parks does not adequately cover all areas of forest (the coastal forests of East Africa are, for example, poorly protected) whilst levels of inbreeding in some protected areas may prove to be unacceptably high, because of their isolation.

4. The environmental history of tropical Africa: past changes in climate and forest

4.1 Sources of evidence

It is now known that marked changes in climate and the extent of forest cover have occurred in tropical Africa over at least eight million years (Hamilton & Taylor, 1991). Evidence for the past extent and composition of forests is available directly from plant fossils, especially pollen and spores, and indirectly from present-day distribution of species. This evidence can be used to reconstruct past climates in tropical Africa, assuming that vegetation is a relatively accurate reflection of overall climatic conditions. Additional non-biological evidence of climatic change in tropical Africa is supplied by palaeosols, and changes in the levels of lakes, the sizes of rivers, the extent of active dunes and glaciers, and from the analysis of stable isotopes in Atlantic and Indian Ocean sediments.

However, there are limits to the degree of resolution possible in the reconstructions of past vegetation from fossils. For example, plant fossils usually comprise only a small fraction of the original flora. Furthermore, the location, number and range of sites where plant fossils are preserved or have been studied is limited (for instance no plant fossils have been described for central Zaïre). Further limitations in the use of evidence from plant fossils arise as a result of difficulties in precise identification, in interpreting the climatic signal contained therein, in dating and as a result of the paucity of evidence for the period prior to ca. 20000 BP.

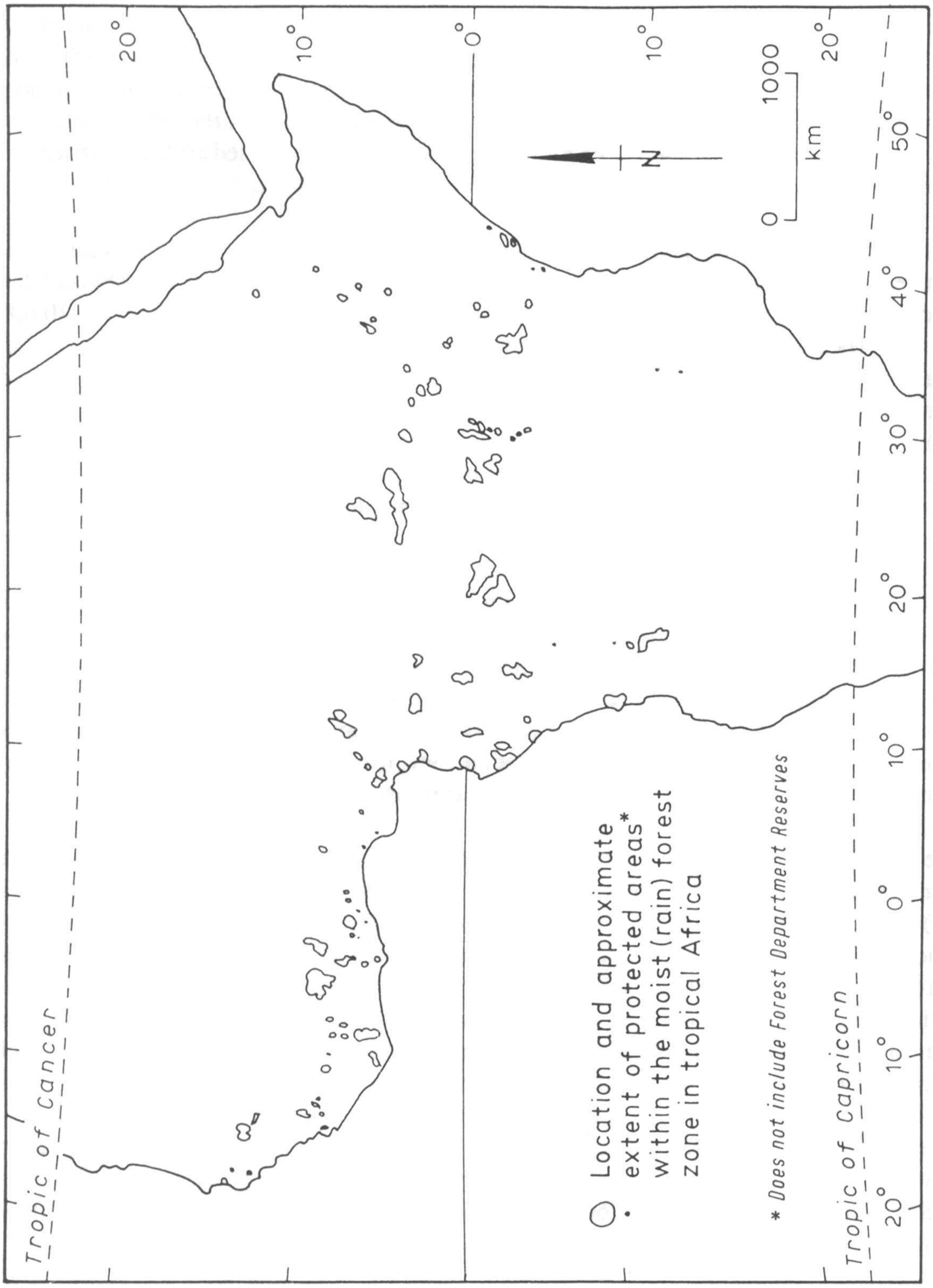

Figure 3.
Location and approximate extent of protected areas (excluding forest reserves) in forested parts of tropical Africa. (Based on data from IUCN, 1992)

4.2 Tropical African climatic history

Evidence from deep-sea cores from the tropical Atlantic shows that climatic oscillations have occurred in Africa since at least the late Tertiary Period eight million years ago, and that these oscillations became more pronounced after approximately 2.5 million years ago (Stein & Sarnthein, 1984). Evidence in Atlantic Ocean cores also indicates wetter conditions in tropical Africa before 6.4 million years ago. Hsu *et al.* (1977) conclude that the drying up of the Mediterranean Sea between 6.4 and 4.6 million years ago caused increased aridity in Africa and brought about a major expansion of savanna at the expense of forest.

The most recent geological period, the Quaternary, covers the last ca. two million years up to the present and is characterised by a series of about 21 major world glacial periods (Shackleton & Opdyke, 1973; vanDonk, 1976), the most recent of which lasted from ca. 70,000 to ca. 10,000 years ago. The glacials are separated by periods of ice retreat, or interglacials, and the cycle of glacials and interglacials is now thought to be driven largely by changes in levels of insolation as a result of variations in the Earth's orbit around the sun (Hays *et al.*, 1976; Imbrie & Imbrie, 1980). Evidence from oceanic sediment cores and climatic models suggests that interglacials have always been warm and moist periods in tropical Africa and that most, but not all, glacials were cool and dry, with aridity becoming most pronounced after one million years ago (Rossignol-Strick *et al.*, 1982).

Most of the available information for conditions in tropical Africa is for the last world glacial period. It is apparent that this period was marked by reduced temperatures and precipitation over much of continental tropical Africa, with maximum coldness and aridity at least since ca. 40000 BP occurring between ca. 21000 BP and ca. 14000 BP (Hamilton & Taylor, 1991). Although it is difficult to be precise, it seems likely that the maximum depression of temperature was at least 6°C and levels of total precipitation were around 30% less than the present day (Livingstone, 1980; Hurni, 1981; Hamilton, 1982; Bonnefille *et al.*, 1990a; Taylor, 1990).

There is evidence for rapid environmental change during the terminal stages of the last glacial period and the early part of the present interglacial (the Holocene). For example, Taylor (1988; 1990) states, on the basis of pollen data, that it became rapidly warmer and wetter in south west Uganda during relatively short periods of time between ca. 14000 BP and 11000 BP, with an apparently abrupt increase in temperature of 3°C at 11000 BP. Changes in climate during the last glacial - Holocene transition in tropical Africa are thought to be due to increased insolation in the Northern Hemisphere, which could have brought about increased precipitation as a result of increased monsoonal activity (Kutzbach & Street Perrott, 1985).

According to both biological and non-biological sources of evidence, tropical Africa appears to have experienced fluctuations in climate during the Holocene. The most significant of these is increased aridity, beginning ca. 6000 BP (Hecky & Degens, 1973; Street & Grove, 1979; Hamilton, 1982; Stager, 1984; Talbot *et al.*, 1984; Lezine & Casanova, 1989).

4.3 The impact of past climatic change on African forests

We know from the plant fossil record that changes in climate forced distributional changes upon forests in tropical Africa, and modified their composition through range expansions, contractions and extinctions of individual species. Long-term increases in aridity during and since the later stages of the Tertiary Period reduced the extent and composition of forests in tropical Africa, as the fossils of some forest taxa now confined to the main tropical forest block in central Africa have been found in northern Kenya and Ethiopia (Bonnefille & Letouzey, 1976; Deschamps & Maes, 1985; Williamson, 1985). Indeed forests may have formed a virtually continuous belt across the continent (Thorne, 1973; Hamilton, 1976). Long-term increases in aridity leading to extinctions of some forest species, have been proposed as a cause of the current impoverishment of the tropical African flora, relative to other tropical regions (Richards, 1973; Hamilton, 1976; 1989a). The rate of climatically induced extinctions may have declined with time, as forest taxa adjusted to generally drier climates. Supporting evidence for this comes from detailed pollen studies on a 2.9 to 3.3 million year old formation in Ethiopia; these reveal a flora of modern aspect, at least at the generic level (Bonnefille *et al.,* 1987). Only two out of the 116 identified pollen taxa do not occur in the modern flora of Ethiopia, and both of these taxa survive elsewhere in Africa. However, climatic change over the last 40,000 years or so appears to have caused local extinctions of non-forest species and modified extant plant communities. For example, fossil pollen records indicate local extinctions of *Stoebe* and *Cliffortia* in south west Uganda (Taylor, 1990), *Artemisia* on Rwenzori (Livingstone, 1967), *Gunnera* on Mount Elgon (Hamilton, 1982) and *Restio* in Burundi and Rwanda (Bonnefille *et al,* 1990b).

During the period of maximum coldness and aridity in tropical Africa, between 21,000 and 14,000 years ago the vegetation in tropical Africa had a very different distribution from that of the present. For example, some taxa were displaced to ca. 1,000 m below their present altitudinal occurrence on the East African mountains (Morrison, 1968; Hamilton, 1972; van Zinderen Bakker & Coetzee, 1972; Taylor, 1990) whilst others descended to altitudes at least several hundred metres lower than today in lowland Ghana (Maley & Livingstone, 1983; Talbot *et al.,* 1984). In addition, there was a major reduction in the overall extent of forests (Livingstone, 1967; Kendall, 1969; Hamilton, 1982; 1987; Bonnefille & Riollet, 1988; Vincens, 1991; Taylor, 1990). During the same period, non-biological evidence indicates a more equatorial distribution of active sand dunes in the Northern Hemisphere (Sarnthein, 1978; Mainquet *et al*., 1980; Talbot, 1980; Sarnthein *et al.,* 1981; Hamilton, 1982). In tropical Africa there was a lowering of levels in lakes and reduced discharges from rivers (Kendall, 1969; Butzer *et al.,* 1972; Livingstone, 1975; Gasse *et al,* 1980; Servant & Servant-Valdary, 1980; Tiercelin *et al.,* 1981; Talbot *et al.,* 1984) and an expansion of glacier ice (Livingstone, 1962; Hamilton & Perrott, 1979).

Although there is fossil evidence for reductions in the extent of forests in tropical Africa and its replacement by drier vegetation types during the last world glacial period, there is little direct fossil evidence to indicate where forests managed to survive (i.e. the location of forest refuges). Instead, evidence is mainly in the form of data on modern distributions of forest taxa. African forests show a pattern of centres of relatively high numbers of species and endemics, separated by more impoverished vegetation (Hamilton, 1976; 1982; 1987; Kingdon, 1990), the areas of highest diversity (otherwise known as 'core areas' or 'hot spots') being in Cameroon-Gabon, eastern Zaïre, east Ivory Coast - west Ghana, Sierra Leone - Liberia and near the coast of East Africa (Figure 4). The core areas tend also to include populations of taxonomically unrelated forest taxa exhibiting disjunct distributions in tropical Africa, the most well known of which is perhaps the gorilla *Gorilla gorilla* which is found on the eastern and western margins of the Congo basin (i.e. the Cameroon-Gabon and eastern Zaïre core areas, respectively) but not in the central part (Hamilton, 1976; 1982).

It would appear that present day differences in climate are partly responsible for the distribution pattern of forest species in tropical Africa, as the clines in species diversity to some extent reflect contemporary gradients of precipitation. However, it is difficult to envisage how many of the disjunct distributions could have arisen if the environment had always remained as it is at present (for example, the central Congo basin appears equally suitable gorilla habitat as its eastern and western margins). Instead, it is now generally accepted that the distribution pattern also reflects major changes in past climate. The core areas are thus assumed to represent forest refuges; areas of relative stability where humid climates and forests were retained during periods of general aridity and forest contraction. Outside the refuges substantial tracts of forest were replaced by vegetation types associated with dry climates, such as woodland, grassland and scrub. The implication that areas within the present tropical forest region having higher rainfall today, also had relatively high rainfall during past arid periods is perhaps not surprising. This is because much precipitation in Africa is orographic (and the overall geography of the continent has changed little over the last ca. 40,000 years or so) and because it is now generally believed that the present pattern of atmospheric circulation over tropical Africa was similar to that of the last glacial period.

Climatic amelioration during the terminal phases of the last world glacial and the early Holocene caused an upward movement of vegetation belts and the replacement of dry grassland and scrub by forests. Similar replacements occurred elsewhere in tropical Africa (Coetzee, 1967, 1987; Livingstone, 1967; Kendall, 1969; Hamilton, 1987; Bonnefille & Riolette, 1988; Vincens, 1991). Differences in climate and soils, the proximity of seed sources and the longevity of resident species meant, however, that forests were unlikely to have been established simultaneously throughout tropical Africa. Since the last glacial period, the forested area in tropical Africa is believed to have reached its maximum during the early part of the Holocene, after which increased aridity since ca. 6000 BP and human activity have brought about a reduction in extent (Lezine, 1987).

5. Current and predicted climatic change in tropical Africa

The evidence for Holocene climatic change comes largely from plant fossils and changes in lake levels. However, meteorological data, written and anecdotal accounts and recorded fluctuations in the extents and depths of glaciers and lakes can be used as sources of information on environmental change during the last 100 years or so. From an analysis of meteorological data, Hulme (1992) states that there has been a trend towards cooler winters and warmer summers in tropical Africa over the last 30 years. This has contributed to changes in the extent of climatic

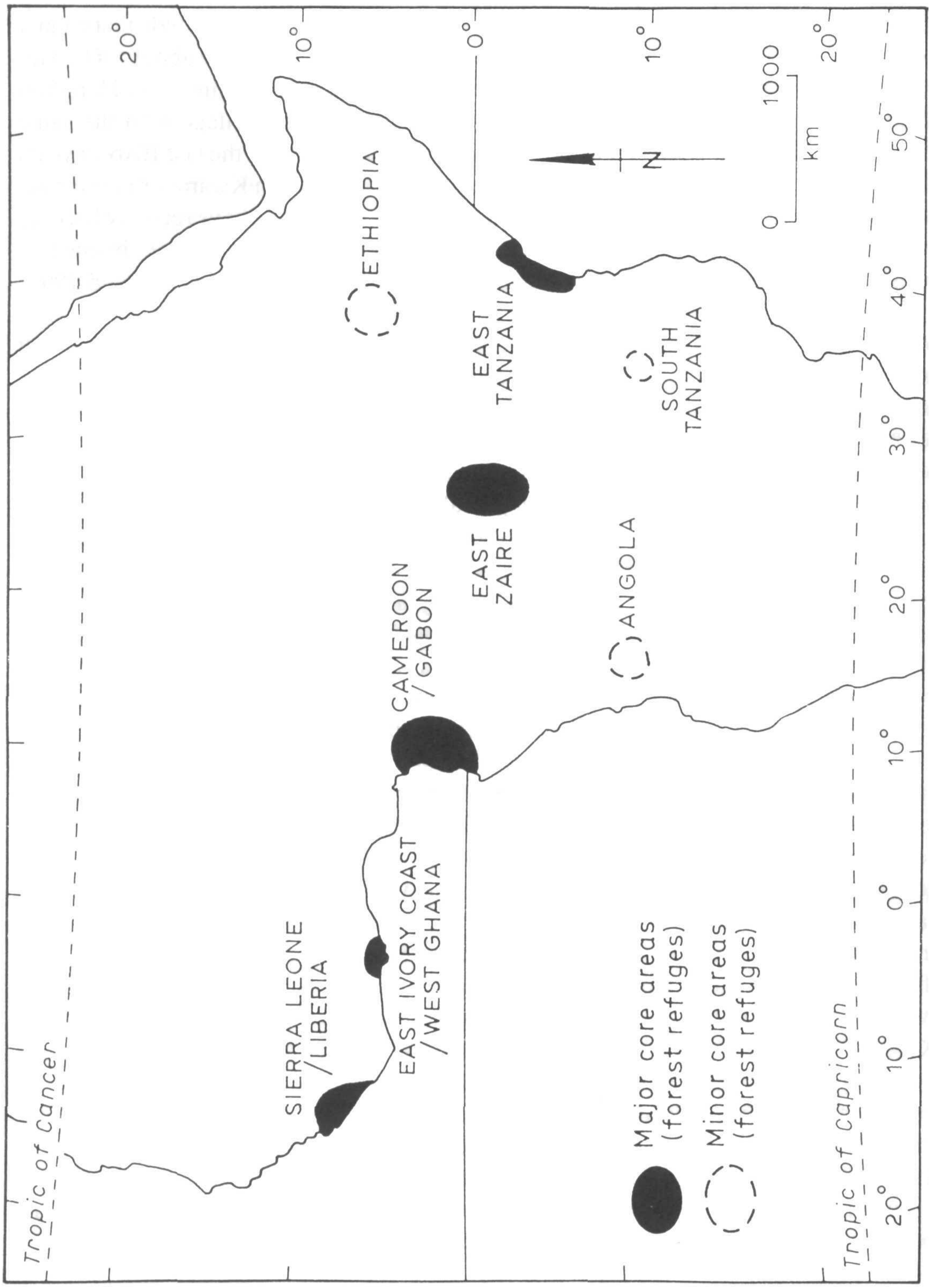

Figure 4.
Approximate location and extent of centres of high species diversity and endemism ('core areas') in tropical Africa. (After Hamilton 1989a)
Core areas possibly coincide with the locations of forest refuges during past ice ages

zones. For example, over the last 30 years there has been a 1.0% reduction of the areas which climatologists, such as Hulme, class as humid and a 1.8% expansion of the areas classed as hyper arid and arid.

On the basis of meteorological records, Hamilton and MacFadyen (1989) conclude that annual rainfall on and around the Usambara mountains has become less reliable since about 1960, with long very dry periods alternating with infrequent very wet years. The conclusion of Hamilton and MacFadyen (1989) ties in with anecdotal evidence supplied by villagers on the same mountains. The villagers also recall that the climate has got warmer over the last 10 to 15 years (Hamilton, 1989b), which is supported by temperature recordings from Kwamkoro tea estate, East Usambara (editors' note in Bruen, 1989). Conditions also appear to have recently become warmer and drier in Kigezi, south west Uganda, according to anecdotal evidence obtained by the authors of the present article during a series of visits to the area between 1980 and 1991.

Some of the recent changes in climate in tropical Africa may well be part of more widely felt changes, particularly those arising through global warming. According to Hulme (1992), global mean annual temperatures have increased by ca. 0.5°C over the last 15 years. These increases will have affected the intensity of atmospheric circulation and rates of evapotranspiration over tropical Africa and adjacent oceans. Climatic models predict that, even if emissions of greenhouse gases are dramatically reduced, global mean temperatures will continue to rise as aresult of the greenhouse effect over the next 100 years (Vellinga & Swart, 1991). The extent of this increase is currently the subject of much debate, although one prediction is that global mean temperatures will increase by around 3°C during the next 100 years, unless controls on the emission of greenhouse gases are forthcoming (Houghton *et al,* 1990). It is unlikely that the rate of increase will be constant, with periods of rapid wanning being separated by relatively stable periods. Regional differences in temperature increase are also predicted, with largest increases possibly occurring at high latitudes in the Northern Hemisphere.

The impact of global increases in temperature on future precipitation levels is still not known because of difficulties in modelling the complex of factors responsible for effective precipitation. To some extent, recent warming and reports of increased aridity contradict the situation in tropical Africa during the early part of the Holocene, when conditions are believed to have been warmer *and* wetter than the present as a result of greater monsoonal activity. However, a tendency towards increased rainfall as a result of increased temperature could have been more than offset by other factors unique to the present, such as large-scale human induced environmental degradation. There is some support for this. Many people on East Usambara and in Kigezi, for example, attribute recent changes in local climate to local forest clearance and swamp drainage. A link between forest clearance and increased aridity has been established in southern Tanzania, where reduced rainfall was noted after 800 km^2 of forests were cleared for agriculture (Pereira, 1973), and on the basis of climatic models (Lean & Warrilow, 1989; Nobre *et al.,* 1990). The link could be through changes in albedo, runoff, the strength of winds and rates of evapotranspiration arising as a result of land degradation. Salati *et al.* (1979) estimate that around half of the local rainfall in Amazonia is derived from local evapotranspiration.

6. The response of forests to current and predicted climatic change

There has been little research carried out to date on the biotic impact of recent fluctuations in climate in tropical Africa. Despite this, some consequences may already be visible. For example, Binggeli (1989) cites climatic change as a potential factor causing large numbers of tree falls and deaths amongst mature forest trees on the East Usambara mountains. To some extent Binggeli's suggestion is surprising considering that the Usambara mountains are part of a region which may, according to Hamilton (1976), have exhibited relative climatic stability. However, a recent expansion of *Maesopsis eminii* out of plantations on East Usambara and into surrounding forested areas could have been facilitated by climatically induced changes in competitive ability amongst native and introduced forest taxa (Binggeli, 1989).

In addition to changes in forest composition, there is anecdotal evidence of an upward displacement of land use in East Africa over the last two decades, which may be a result of wanner climates. For example, mangroves and coconuts on the Usambara mountains and bananas in Kigezi are now cultivated at higher altitudes than was previously possible. Increases in temperatures on the eastern Usambara mountains may have also caused the increased incidence of malaria there, at altitudes above 1,000 m (Matola *et al.*, 1987).

Uncertainties over changes in the levels of effective precipitation make accurate predictions of the response of forests to future climatic change difficult, particularly as regional variations are likely. If the area of humid conditions in tropical Africa continues to contract then reductions in the extent of forests are to be expected. There is widespread agreement that global temperatures will continue to rise over the next 100 years and this increase may, as in the past, cause vertical shifts in vegetation in tropical Africa. Alternatively, as periods of climatic warming in the past appear to have been associated with increased levels of precipitation, significant increases in temperature in the future with concomitant increased aridity, may not simply result in shifts of vegetation to higher altitudes.

7. The implications of predicted climatic change for forest conservation in tropical Africa

Forests have survived very major changes in climate throughout the Quaternary period, responding by changes in composition and distribution. From the fossil record, it would appear that no plant extinctions have occurred either at the family or generic level as a result of climatic change over the last 40,000 years or so. In view of their apparent resilience, a question that immediately springs to mind is whether there are grounds for concern over the future of tropical African forests in the light of predicted future climatic change?

Although the response of forests in Africa to past changes in climate is reassuring, at least at first sight, such optimism must be tempered by the fact that there are no exact analogies in the past for today's environmental changes, given the prominent impact of humans on the environment at present. Predicted rates of climatic change may well be greater than have occurred since the last ice age, at least for the tropics (Houghton *et al.,* 1990). However, as information concerning the detailed (i.e. century-scale) rates of past climatic change is largely lacking, it is possible that forest species have survived rates of climatic change in the past at least as rapid as those at present and predicted for the future, simply by changing their distribution. Much more worrying is the likelihood that human pressure will prevent similar changes from taking place, thus forcing many species to become extinct. For example the large tracts of agricultural land and modified rangeland that exist today in tropical Africa are, by occupying land suitable for forests and by acting as a barrier to dispersal, likely to prevent many forest species from taking advantage of new opportunities afforded by changes in climate. A major wave of extinctions could result if climates become unfavourable for forests in presently forested areas while at the same time dispersal is being restricted. Indeed, the dispersal ability of forest species across inhospitable terrain is likely to be a major factor limiting the response of forests to future environmental change. The current distribution patterns of species in tropical Africa in which core areas are separated by more impoverished forests are possibly an indication of just how slowly many species are capable of responding to climatic change, even through what is regarded as suitable habitat.

On the basis of past evidence it would seem that, if permitted, forests are able to survive periods of relatively rapid climatic change in a more or less intact state. There is no doubt that the continued clearance and utilisation of forests and future changes in climate will bring about further changes in the distribution and composition of forest in tropical Africa. However, uncertainties concerning the exact nature of future climatic conditions makes predicting the response of forest species and choosing the best location and management strategy for protected forest areas a very difficult task at present. It would therefore seem judicious to continue research into the ecological requirements of forest taxa and into the nature and rate of future changes in climate and the response of plant and animal communities. This information will allow us to predict with more confidence the nature of climatic conditions and species' distributions in the future. For example, the increased precision of climatic predictions will require a much more complete, instrument-gathered meteorological data set on which to base and validate existing and future models, and therefore financial and scientific support for existing and new systems for monitoring the weather. Secondly, there is a need to assign a high priority protection to areas that are believed to be climatically more stable, as these are least likely to suffer from the effects of future climatic change. The present day conservation value of these areas is further increased because they are also relatively species and endemic rich. However, as the precise number, location and extent of core areas is currently in doubt, research in the form of biogeographical surveys is first needed to accurately determine their position 'on the ground'. Thirdly, individual protected areas must be of adequate area and include broad gradients of both temperature and effective precipitation, so as to allow species therein to accommodate to climatic change. Preferably protected areas will be connected by corridors of forests, thus reducing the effect of isolation and enabling the natural exchange of genetic material. Ideally these corridors of forest would be managed in a sensitive way, such as along the lines of multiple use areas in biosphere reserves. Finally, conservationists must consider more positive management of protected areas as a means of helping forests survive rapid climatic change. For example, *ex situ* propagation should be promoted to provide for replenishment planting and species re-establishment, as should the human-assisted dispersal of forest species.

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Potential impacts of rapid climate change on coral reefs: implications for marine parks

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Abstract

Coral reef ecosystems are subject to serious and increasing short-term anthropogenic stress in many areas. The longer-term effects of global climate change are of concern, but have only limited predictability. They are likely to be most damaging in reef areas already subject to non-climate stress. Effects of climate change are most likely to be seen in community responses to changes in the nature, intensity, or frequency of extreme events. In healthy communities, the reef ecosystem is likely to recover, although there may be shifts toward community dominance by benthic organisms with shorter lifespans and greater tolerance for high temperatures and/or high energy environments; in communities undergoing non-climate stress (such as nutrient loading, sedimentation, overfishing), there may be a shift from coral-algal calcifying benthos to erosional and non-calcifying reef communities, and ultimate loss of the coral reef ecosystem. The global threat to coral reefs by probable higher temperatures, reduced carbonate saturation states, and elevated ultraviolet radiation is cause for concern but not despair. In view of the uncertainties, park selection and management strategies must "tie-in" long-term protection against the known problems of climate change with closely related but even more urgent measures required to protect against short-term destruction by other factors. Guidelines for park management and planning should include: a) criteria for selection of sites and extent of new parks; b) avoidance or reduction of local anthropogenic stress; c) consideration of the effects of changes in areas distant from the protected areas; and d) coordination and collaboration between parks and coral reef research scientists to provide the careful assessment, monitoring, and planning updates useful to both.

1. Introduction

In order to discuss the implications of rapid climate change for marine parks, I will consider parks almost exclusively in terms of their conservation role - as a means for ensuring the local (and possibly global) survival of ecosystems and the organisms that constitute them - even though I am well aware that parks may serve many other functions. As the most conservative reasonable climate change prediction, I adopt the "Business as Usual" scenario predictions of the Intergovernmental Panel on Climate Change (Houghton *et al.,* 1990). After briefly discussing background information and concepts, the major aspects of climate change, and the characteristics of reefs that govern their responses to climate change, I will make two sets of recommendations: first, principles for the design or selection of a new coral reef park or reserve in order to provide the best long-term protection against climate change; and second, a necessarily somewhat smaller set of suggestions for the management of existing marine parks.

Hatcher *et al.* (1989) have prepared a thorough review of the research literature relevant to the conservation of shallow tropical marine ecosystems. Soule (1991) has analysed conservation strategies and techniques; since most of the world's coral reefs are in developing countries, his discussion of the utility of various conservation techniques as a function of political stability, population pressure, and various aspects of development are particularly relevant. Smith and Buddemeier (1992) review the possible coral reef ecosystem responses to various aspects of global change, both climatic and otherwise.

2. Climate and environmental change

Under the IPCC "Business as Usual" scenario (i.e., no substantial changes in present trends in greenhouse gas emissions), global mean temperatures are predicted to increase during the next century by about 0.3°C per decade (range: 0.2-0.5°C). The net increase will amount to about 1°C by 2030 and 3°C by 2100. Land surfaces will warm faster than oceans, and high northern latitudes will warm more and faster than the global mean, especially in winter.

Present confidence in regional climate change predictions is low. In the oceanic tropics, the predictive ability of the present climate models is highly questionable; both between-model agreement and calibration against present conditions are poor. At least some models predict sea-surface temperature increases of 1-3°C for a doubling of atmospheric CO_2, but there is widespread debate about possible temperature-limiting feedback mechanisms (Heymsfield & Miloshevich, 1991; Ramanathan & Collins, 1991). Although paleoclimatic conditions are not generally considered reliable predictors of future climate patterns, it may be relevant that during the Eemian warm period (125,000 years ago), most northern hemisphere land areas were significantly wanner than at present, but tropical regions were not detectably warmer (Ruddiman, 1985; MacCracken *et al.*, 1990). This can be interpreted to mean either that the tropics may not warm significantly, or that if they do warm the effects are likely to be catastrophic because organisms and ecosystems have not had recent evolutionary experience with similar extremes.

Global eustatic sea level rise, under the IPCC "Business as Usual" scenario, is predicted to average about 6 cm/decade over the next century (range: 3-10 cm/decade); this value compares with recently observed values of 1-2 cm/decade, and with maximum sustained rates of sea level rise during the Holocene transgression in excess of 20 cm/decade (Fairbanks, 1989; Bard *et al.*, 1990).

Changes in the frequency and intensity of extreme events are probably more ecologically significant than moderate changes in the mean values of environmental factors. In addition to a probable increase in high-temperature events, two other possible changes are relevant to local coral reef environments: a shift in precipitation patterns so that a larger fraction of the total precipitation falls during heavy storms; and a possible change in the frequency, magnitude, or geographic distribution of major tropical storms. A possibility not addressed by the IPCC has been discussed by Broecker (1987), who pointed out that changing climate may result in major shifts in oceanic circulation patterns such as currents and upwelling.

Aspects of global change that are not strictly climatic but potentially significant are the expected increases (1-10% in the tropics) in surface exposure to ultraviolet radiation, and decreases in surface ocean pH and carbonate mineral saturation state in response to equilibration with increased atmospheric CO_2 concentrations (Smith & Buddemeier, 1992).

3. Coral reef ecosystem and response characteristics

Reefs are commonly associated with warm (>18-20°C), shallow (to a few tens of meters), clear, low-nutrient waters, and hard substrates (commonly of their own creation). They are well adapted to natural disturbances (Grigg & Dollar, 1990) and have survived Quaternary climate fluctuations with extinction rates near background levels (Paulay, 1991). In spite of their apparent robustness in the natural environment, coral reef ecosystems seem quite vulnerable to anthropogenic disturbances, particularly those such as nutrient loading or increased sedimentation that alter either the substrate or the competitive advantage of other communities such as soft corals, macroalgae and bioeroders. Indeed, there is widespread evidence and agreement that coral reefs are being destroyed and degraded at a rapid rate by overexploitation, contamination, construction, poor land use practices, and so on (Wells, 1988; Hatcher *et al.,* 1989).

From the standpoint of evaluating the responses to environmental change, reef ecosystems have several important general characteristics.

a. *Calcification.* Coral reef systems produce copious amounts of calcium carbonate; near-maximum calcification rates may extend to depths of as much as 20 m under favorable conditions, and their ability to "grow" in a geologic sense has been one of the mechanisms by which they have survived past sea level changes. This has been reviewed by Buddemeier and Smith (1988), although in the context of sea level rise predictions much higher than are now considered realistic. In subjective terms, the health and abundance of calcifying corals and algae are probably key indicators of the "quality" of a coral reef ecosystem.

b. *Temperature sensitivity.* Although coral reefs occur normally only in relatively warm waters, it is also recognised that many corals live close to their upper temperature limit, and unusually elevated temperatures induce stress and mortality (Jokiel & Coles, 1990; Glynn, 1991). It is also clear that adaptation or acclimatisation to some greater degree of temperature elevation or variation is possible in many situations, but unfortunately the mechanisms and possible rates of these processes are unknown (Smith & Buddemeier, 1992).

c. *Intrinsic time and space scales.* Reefs are influenced by factors at a wide variety of time scales (Hatcher *et al.,* 1987), but one of the critical time constants is the lifespan or community succession time of the major reef-building corals, which is typically in the range of several decades to a few centuries. This has several implications: it is relatively long compared to the period of sustained scientific study of reefs; it is of the same magnitude as some of the anticipated climate changes; and it promotes analogies with terrestrial forest systems. Although useful in some ways, the spatial scales of reefs are quite different from expectations based on forest analogies. Individual reefs have scales of tens to hundreds of meters; extensive barrier or fringing reefs may be longer than this, but there is often relatively little lateral interaction or interdependence in such quasi-linear systems. If individual patch or community sizes are small by forest standards, the effective range of recruitment is much larger, since many reef species reproduce by a larval stage that may be transported tens or even hundreds of kilometers before settlement. This partly accounts for ecosystem resilience in response to episodic disturbances. Issues of scale and survival have been reviewed by Buddemeier and Hopley (1988).

d. *Diversity and variability in habitat and response.* Reefs have high biodiversity for a marine system. They tend to show very consistent structural features and community metabolic responses (Crossland *et al.,* 1991; Kinsey & Hopley, 1991) over a wide range of environmental and biogeographic conditions, indicating probable resilience with respect to the loss of individual species. Because of the steep environmental gradients (Smith & Buddemeier, 1992) and structural complexity in the coastal zone, a reef system that extends from a coastal fringing reef through a lagoon to the oceanic forereef of a barrier can exhibit extreme habitat or micro-environment diversity (Huston, 1985), both in general and with respect to stresses and stress responses. The apparent paradox of reef robustness with respect to natural disturbance and fragility with respect to some anthropogenic stresses has been discussed above.

4. Short- versus long-term survival

Reefs have demonstrated survival on natural geologic and climatic time scales (cycles of thousands to tens of thousands of years for periods of millions of years). Greenhouse-induced climate change is expected to occur on a time scale of decades to centuries - much faster than the natural changes to which the ecosystem is adapted, and on the same time scale as community turnover times and coral lifespans. However, we also recognise that reefs are currently subject to anthropogenic destruction and degradation on time scales of years to decades. The climate change equivalent to a doubled CO_2 atmosphere is not expected until the middle of the next century, and Wigley and Barnett (1990) estimate that it will be a decade before the greenhouse "signal" is reliably detected above the noise of climatic variability. Under these conditions, and given the uncertainties in the regional climate change predictions, we must ask ourselves whether it is a practical use of limited resources to concern ourselves with long-term, climate-related conservation strategies when the short-term survival of coral reefs may be in doubt. My answer to this question is a definite yes, but I emphasise that this must be as a part of an integrated approach to both short-term and long-term conservation. The robustness and resilience of coral reef ecosystems are characteristics that we can turn to advantage in compensating for their fragility and vulnerability; not only can we hope to protect reefs by judicious selection and management, but we can hope to restore them by removal of stress (Evans *et al.,* 1986) or even more manipulative techniques. Through these means, we can look forward to greatly improved scientific understanding of both coral reef dynamics and the nature of climate change as time progresses. In this spirit, I will outline briefly the climate change responses of greatest concern over the period of the next century, and then proceed to recommendations and conclusions.

5. Reef responses to climate change

Three global change variables are expected to be truly global in distribution and direction of change, and in two cases, in magnitude of change. The expected increase in eustatic sea level over the next century is well within the accretion capability of healthy reefs, and may actually improve conditions for reef growth where sea level or restricted water circulation are currently limiting. Even for reefs that are not healthy, the inundation over the next century will be a small fraction of the potential depth of optimum growth. The major concern related to sea level rise will be secondary effects, such as the existence of erodable shorelines, which might produce sedimentation stress. The increase in atmospheric CO_2 concentration may reduce calcification rates by making the tropical surface ocean water less supersaturated with respect to the carbonate minerals, although we do not know enough to be make predictions with confidence. Ultraviolet radiation can stress marine organisms, and there is concern that even the modest increases expected in the tropics may inhibit reproduction or cause additional direct stress to reef organisms. In this case also, there are not enough data to make useful predictions. For all of these truly global and seemingly inevitable changes, little can be done beyond minimising other forms of reef stress and monitoring for effects. Fortunately, none of these factors is likely to be lethal on a system-wide basis on the time scales I am considering.

Of the other climate-related environmental variables, only temperature can be said to have a probable global trend. Although elevated temperatures certainly stress coral, it is important to recognise that the stress is due not to increase in the mean value but to the occurrence of unusually high temperature events. Temperature stress thus falls into the same category of altered frequency of extreme events as do major storms and floods. For such variables, the appropriate strategy is to manage the environment in such a way as to preserve or enhance the reef system's natural capability to recover from episodic brief disturbances. It should also be noted with respect to temperature that warming of higher latitude waters may make currently marginal reefs more viable. Extreme but permanent events such as major ocean current shifts are unpredictable even on a statistical basis, and cannot therefore be the focus of specific preparations. It is not currently practical to identify limiting rates of climate change or to identify specific regions that are more or less vulnerable, although such abilities may develop over the next decade or so. This is because the dominant stress factors are statistical in nature, non-climate stress factors are so important, climate predictions are uncertain, and our knowledge of the effects of those climate factors that are reasonably predictable are also uncertain.

A final category of reef responses is to secondary stress-problems caused by the interaction of climatic factors with another ecosystem on which the reef depends. A specific example is the common proximity of reefs to seagrass beds and/or mangroves. Loss of either of the other two ecosystems is likely to place stress upon the reef because of its increased exposure to terrigenous effects from which it was previously protected (Hatcher *et al.,* 1989). This illustrates the importance of local assessment and protection or control of neighbouring environments.

6. Guidelines for new or expanded parks

I recognise that few, if any, of the readers of this paper will be in a position to define or design new parks, but this is a convenient way to stress the kinds of principles that should be considered in all settings, even though they may frequently be compromised for practical reasons. The basic points are addressed by a key word or phrase and a brief comments.

a. *Remoteness.* The primary concern is remoteness from present and probable future major sources of anthropogenic stress, such as urban areas, industry, intensive agriculture or and deforestation. The motivation is to avoid the chronic and compounding stresses that make reefs less able to recover from natural disturbance or the effects of climate change. It should be remembered that remoteness is an oceanographic concept as much as a geographic one - a short distance up-current or along a well-flushed open coast may make a reef more remote than a much longer distance down-current or in an enclosed embayment.

b. *Condition and cause.* Conservation measures are often called into play only after substantial damage has occurred. If the damage is due to chronic and increasing anthropogenic stress that is beyond control, the question must be asked as to whether efforts would be better spent on reefs that could be saved or rehabilitated. If the environment is marginal in large part because of climatic factors that may ameliorate with climate change, then preservation of possible future reef sites may be justified. Careful initial assessment can affect both selection and management.

c. *Habitat variety.* Protection of only a fringing reef or a coral cay sacrifices some of the diversity that makes large reef systems resilient. If possible, inclusion of a range of habitats including fringing reefs, patch reefs, and barrier or shelf-edge reefs will not only increase the protected biodiversity, but will ensure a greater range of adaptations and stress tolerances.

d. *Size and replication.* Many extreme events (such as storms, floods, *Acanthaster* outbreaks) have intrinsic spatial scales - from as little as the size of a single reef to tens of kilometers. Reserve areas that are either large enough or sufficiently numerous and separated so that a single event does not destroy the entire protected area are another strategy for taking advantage of the reef ecosystem's natural tendency to recover.

e. *Recolonisation potential.* Because larval transport can result in replenishment and recolonisation of reefs, it is useful to consider directions of transport and to attempt to protect source areas. As a regional example, we know from circulation patterns in the Caribbean that healthy reefs in the southeastern portion of the sea have the potential for recolonising most of the Caribbean and Gulf region, whereas preservation of reefs in Florida or Bermuda might do little to provide natural recruitment in the southern and eastern portions of the basin. The same principle can be applied at virtually all scales.

f. *Adjacent ecosystems.* At the environmental level, are there interactions with the reefs that would dictate protection of larger, non-reef areas (as in the seagrass and mangrove example discussed above)? In a political or legal sense, can control over potentially conflicting or damaging uses of adjacent areas be obtained?

7. Guidelines for existing parks

A primary suggestion is to evaluate existing parks according to the above guidelines to obtain a realistic evaluation of present condition and future prospects. As an extreme example, it might be possible to sell or trade a hopelessly degraded park near an expanding urban centre for a more remote location with greater conservation potential. Other actions could include:

a. *Addition.* Needs for either additional territory or additional legal powers and controls should be identified and justified, whether or not they are immediately feasible. Unfortunately, we may expect continued environmental degradation; this will build additional pressure for protection, so it is desirable to have plans developed in case of need or opportunity.

b. *Monitoring and assessment.* It is extremely important to understand conditions and trends within the park, from both the technical and political perspectives. Fortunately, coral reef researchers have recognised the importance of long-term observations to understanding many reef problems (IOC, 1990; D'Elia *et al.,* 1991), and it should be possible to establish mutually beneficial relationships between park managers and research or monitoring groups. Key actions by park managers might include facilitation of permits for scientific studies, provision of basic operating facilities (laboratory or storage space, boat), and communication with the growing network of reef-related regional or global programs.

c. *Assessment reviews and planning updates.* The field of climate change predictions and observations is evolving rapidly, and the interest in coral reef monitoring and research promises new discoveries concerning both organism and ecosystem responses. Park management cannot afford to remain technically static.

d. *Protection and rehabilitation.* For parks that may not be optimally situated or in good condition, the importance of minimising present and future non-climate stresses cannot be over-emphasised. In areas where alternative conservation sites are unavailable and degradation is serious, restoration ecology projects may be considered, particularly if organisms or strains more resistant to the dominant stresses can be identified.

8. Summary and conclusions

Schneider (1989) has advocated a "tie-in strategy" with respect to reduction of greenhouse gas emissions - doing those things that reduce the threat of climate change, but at the same time providing cost-effective responses to other, short-term, societal problems such as air pollution, energy conservation, the need for investment in advanced technology research and development. I have tried to point out a similar strategy in an environmental sense - virtually all of the guidelines suggested serve to protect parks and reserves from the more immediate short-term anthropogenic threats. Not only do they do that, but in the process they provide the best protection we can realistically offer against the real but very poorly predictable longer-term threats of accelerated climate change.

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