GLOBAL Climate Change and Biodiversity

Edited by
Rhys E. Green, Mike Harley, Lera Miles,
Jörn Scharlemann, Andrew Watkinson and Olly Watts

RSPB WWF ENGLISH NATURE UNEP WCMC Tyndall°Centre for Climate Change Research

Global Climate Change and Biodiversity

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Summary of papers and discussion

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Introduction

The Earth's climate is changing and the impacts are already being felt by biodiversity and wildlife habitats across the planet. This summary report from the international conference *Global Climate Change and Biodiversity* presents some of the latest scientific research into how the natural world is being affected by climate change – and also how the natural world might respond in the future.

This conference was the third in a series, begun in Boulder, Colorado in 1997, for scientists and others working on the impacts of climate change on biodiversity. Individual sessions of *Global Climate Change and Biodiversity* covered a cross-section of the planet's major biomes: forests, marine, high latitudes and montane, managed landscapes and coasts. The impact of climate change on natural systems was shown to vary in different ecosystems in different parts of the world. But the overriding message of the conference's summary discussion session is that climate change is all-pervading and will have an increasing influence on the life systems of the Earth.

The conference, held at the University of East Anglia in Norwich, UK in April 2003, was organised jointly by the RSPB, WWF-UK, English Nature, UNEP-World Conservation Monitoring Centre and the Tyndall Centre for Climate Change Research.

Global climate change: climates of the future, choices for the present

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Global climate: past, present and future

The climate of the Earth has never been stable, least of all during the history and evolution of life on Earth. Recent glacial periods, for example, have been (globally) 4°–5°C cooler than now, and some interglacials have been (perhaps) 1°–2°C warmer. These prehistoric changes in climate were clearly natural in origin and occurred on a planet inhabited by primitive societies with far smaller populations than at present. Indeed, the regularity of the diurnal and seasonal rhythms of our planet has always been overlain by inter-annual, multi-decadal and millennial variations in climate, over whatever timescale climate is defined. Ecosystems and species have moved, often freely, in response to such past changes and have evolved within this climatic history.

The causes of contemporary and future changes in climate, their rate and their potential significance for ecosystems and for the human species, however, are all notably different from anything that has occurred previously in history or pre-history. Evidence of global warming is plentiful and includes data on satellite-measured sea level change (2 mm rise per year from 1993–2003), lengthened growing season (by two to three weeks in the past 15–20 years) and increased precipitation intensities resulting in increased flood risk during winter in the northern hemisphere. The *causes* are now dominated by human perturbation of the atmosphere and the *rate* of warming already exceeds anything experienced in the last 10,000 years. It is set to become more rapid than anything experienced in recorded human history and, given the ecological imprint made by our current and growing population of six billion and more, the *significance* of this prospect for the natural world and for human society is qualitatively different from previously experienced changes in climate.

The nature of the problem

The atmosphere delivers both resources (eg rain, sun, wind) and hazards (eg hurricanes, blizzards, droughts) to ecosystems and societies. Through autonomous and/or planned adaptation, species and individuals, ecosystems and societies, are fashioned to a considerable extent by these climatic constraints. Ecosystems and our human cultures and economies are 'tuned' to the climate in which they evolve. Yet highly successful cultures develop in varying climates: cold/dry climates (eg Finland), cold/wet climates (eg Iceland), hot/dry climates (eg Saudi Arabia) and hot/wet climates (eg Hong Kong) (see Figure 1). All societies have therefore evolved strategies to cope with some intrinsic level of climatic variability – for example, nomadic pastoralism, flood prevention, building design, weather forecasting, early warning systems and the weather-hedging industry are all forms of human response to the variability of climate or the extremes of weather. Similarly, ecosystems are resilient to some extent of climatic variability, indeed may actually require it. Consequently, there exists some level of variation in climate or some frequency or severity of weather extremes that can be 'accommodated' using existing strategies or behaviour. Exactly *what* can be accommodated, however, varies greatly within and between societies and ecosystems, so that vulnerability to weather and climate change is strongly differentiated. For example, in developed, northern nations, it is the elderly who die during heat waves, and in developing countries, it is often the poor and marginal who have their homes washed away in shanty towns built on flood plains.

So the central concern is *not* that humans are altering climate – we have modified our environment to a marked extent throughout our history – but *whether* these changes in climate can be accommodated using our existing capacity to adapt, drawing upon our intellectual, regulatory, social or financial capital and *whether* ecosystem resilience is large enough to survive these climatic perturbations given the other pressures they are subjected to by human development. An important supplementary question is whether we can consciously enhance this adaptive capacity, especially of the most vulnerable ecosystems and communities, to exploit the changing resources and minimise the changing hazards delivered to us by our (now) semi-artificial climate. Additional questions that flow from this perspective are: to what extent can we (need we?) predict future climates to assist this process of adaptation, and to what extent do we need (and desire) to reduce the size of the changes in climate facing us to allow our adaptive potential to sustain an acceptable dynamic equilibrium between climate, ecosystems and society?

Rising to the challenge

We face certainly continuing, probably accelerating and possibly unprecedented changes in the Earth's climate over the coming years and decades. These changes in such a fundamental resource for society, and in such a powerful influence on ecological, economic and cultural development, will introduce new challenges for the way we live with and influence climate. Some of these challenges may be broadly foreseeable, many of them may not. Some of the risks associated with a rapidly changing climate may be quantifiable, many of them may not. What should our response be?

As evidence is emerging that some physical and biological systems are already reacting to this human-induced change in climate, and as we know that, at least for some regions and for some communities and ecosystems, climate variability already imposes huge costs, doing nothing is unlikely to be the best option. Societies need to develop and implement appropriate strategies to reduce the risks associated with a changing climate – to ensure that these changing climatic resources are appropriately exploited and that the adverse impacts of changing climatic hazards are minimised.

Mitigation measures are required to reduce global greenhouse gas emissions with the intention of eventually stabilising atmospheric concentrations at some level at which an acceptable dynamic equilibrium could be sustained between climate, ecosystems and human society. What this level ought to be, however, remains poorly known and increasingly contested. On the other hand, due to the inertia of both the climate system and our energy structures, greenhouse gases accumulated and accumulating in the atmosphere since the pre-industrial era will continue to affect global climate long into the future. Together with the existing exposure of many communities and assets to extremes of weather, adaptive measures become essential in order to enhance the coping abilities of valued ecosystems, vulnerable communities and exposed infrastructures.

These crucial perspectives about climate change need to be integrated fundamentally into the full range of policy measures that are demanded by our drive towards sustainable development, an argument equally valid for the nations of the south as for the nations of the north. We all need to come to terms with climate change.

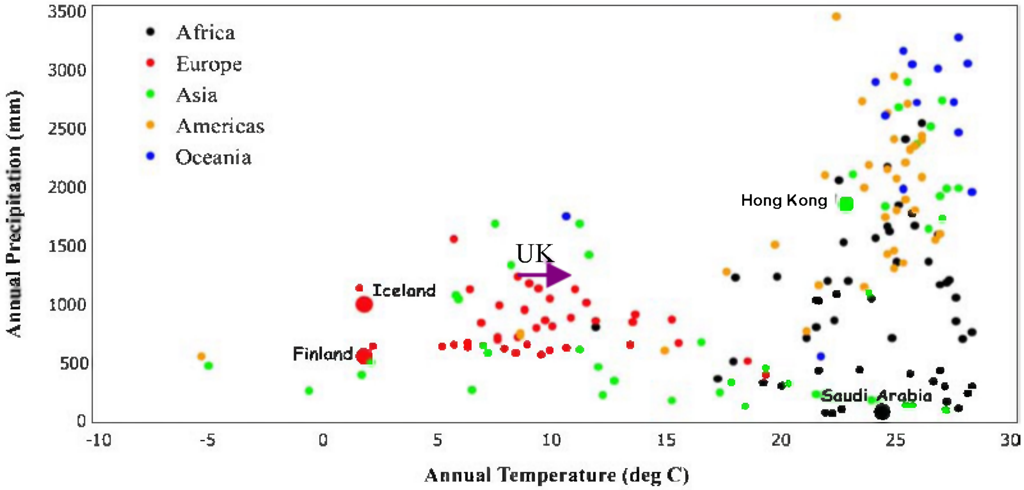

Figure 1. Geographical variation in current climate illustrated by a plot of annual precipitation against mean annual temperature for many locations worldwide. By the 2080s, the UK climate will be more similar (in a crude sense) to that of Croatia or South Korea as indicated by the right-pointing arrow.

Modelling global change effects on vegetation and exploring our vulnerability

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The first part of this paper assesses the changes in carbon storage in terrestrial ecosystems, on global and European scales, considering potential and actual vegetation cover and soils. The second half then looks at the vulnerability of people and society to these and other global changes.

A model for predicting the effects of changes in both climate and atmospheric CO_2 on global vegetation is used (LPJ-DGVM, the Lund-Potsdam-Jena Global Dynamic Vegetation Model). Taking latitude, climate, soil texture and CO_2 as the input variables, net primary production, soil respiration and the terrestrial carbon pool can be calculated and the terrestrial carbon balance can be expressed as Net Ecosystem Exchange (NEE). To give an example of the performance of the model, the close fit of simulated and observed NEE was presented for four sites ranging from latitude 49°N to 64°N.

Global model runs for potential vegetation driven by five different scenarios (IS92a emissions and climate calculated by five different Global Climate Models (GCMs)) were presented. The calculations do not yet consider land use changes. Nonetheless, the future projections do contain some noteworthy general statements. The first is that the global tree line will extend northwards, squeezing the current extent of the tundra. Second, southern latitudes will become increasingly sensitive to drought stress, which is likely to be an important impact on tropical forests (in addition to anthropogenic exploitation).

The modelling of actual vegetation change, taking into account land use changes and other human management, is more difficult. However, especially in Europe, anthropogenic influences on land use and land cover should not be neglected. Therefore, European trends have been run using the actual current land cover and 16 climate change scenarios (from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios A1fi, A2, B1, B2 emissions and climate calculated by four different

GCMs). The range of temperature increase across the scenarios is between 3°C and 6.5°C. Precipitation change forecasts show an overall declining trend of approximately –3% change in precipitation over the 21st century, with steep troughs of almost –8% precipitation change in the 2050s and a smaller trough (around –5% change) in the 2090s (to include variability which is not given by GCM results, the climatic variability of the 20th century is repeated in the climatic projections). Model runs clearly show a decline of the current European carbon sink over the 21st century, although by the end of the century Europe's terrestrial ecosystems are projected to remain a carbon sink. The range of results from the different scenarios, however, extends over the carbon neutral line in the event of extreme climatic change. Comparing different climatic projections for a given emission scenario (eg SRES A2) shows considerable variations of the European carbon balance in most regions, reflecting the variation among the four climate scenarios.

In concluding the first section, we can say that climate change is likely to cause the forest line to extend north. There is high variability between the different scenarios; nonetheless, there are some trends in net ecosystem exchange. Most European forests will continue to be carbon sinks, but the extent of this sink is decreasing. The Mediterranean area is the most sensitive to drought factors.

The extent to which these changes matter to people and society is important to consider. Ecosystems provide many services to people, from food production, water storage and flood prevention to recreation, tourism and beauty. The biodiversity of ecosystems is important in its own right, in its contribution to the services we expect of ecosystems, and for the spiritual needs of people. Assessing vulnerability to climate change is important, both to inform stakeholders of possible changes and potential harms, and to encourage sustainable management to balance environmental, social and economic interests in the long term.

This endeavour requires natural and social scientists to work together and to find ways to integrate qualitative and quantitative measures of how we project our future to unfold. Vulnerability, or the potential for harm, can be assessed as a function of exposure to change, ecosystem sensitivity and the adaptive capacity of both people and biodiversity. Exposure includes emissions changes, climatic change itself, land use change and nitrogen and phosphor deposition. Sensitivity can be assessed through coupled human-environment models such as LPJ-DGVM. For adaptive capacity, macro-scale indicators of socio-economic wellbeing are used – model development in this area of research has only just started.

The EU-funded ATEAM project (http://www.pik-potsdam.de/ateam) is taking forward a methodology for vulnerability assessment, bringing all these factors together. Dialogue between scientists and stakeholders is central to the process. Multiple scenarios of change in climate, land use and nitrogen deposition drive a modelling framework that projects changes in ecosystems on a 10′x10′ grid scale. Furthermore, downscaled socio-economic indicators from the SRES are combined to project changes in adaptive capacity (ie the ability to implement planned adaptation measures). Combining these two outputs generates maps of vulnerability, providing both stakeholders and scientists with assessments of vulnerability that will provide a direction for sustainable management.

We can conclude that the sensitivity of ecosystems can lead to vulnerability of human sectors, wherever people rely upon or use any of a variety of ecosystem services. This calls for a balanced stakeholder dialogue. Assessing vulnerability to global change requires us to understand and predict exposure, sensitivity and adaptive capacity to change. Given the uncertainty of any future scenario, assessments of vulnerability should use multiple scenarios to allow the best assessments of trends and range of change.

Vulnerability information can then guide stakeholder approaches to understanding the future for ecosystem services, coping mechanisms and interactions, and facilitate sustainable management.

Models of the global impact of climate change on biodiversity and adaptive responses

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Recent reviews demonstrate a high confidence that climate change effects are already showing in living things. Despite this, there have been few attempts to model climate change impacts on biodiversity at the global scale.

Change in biome area simulated by coupled Global Circulation Models (GCMs) and Global Vegetation Models (GVMs) may be used to estimate changes in species richness, if the assumption is made that species are faithful to their biome. That is, the biome's climatic definition is assumed to be a proxy for the climatic envelope of multiple resident species.

Changes in biome areas were examined under two scenarios: 1) shifts in biomes kept pace with shifts in climatic conditions and 2) biomes fail to shift to new areas due to migration limitation. In addition, estimated future migration rates are compared with post-glacial rates, and are used to locate areas that may be disproportionately important in facilitating future migration. Biome mapping was undertaken using 14 combinations of seven GCMs and two GVMs.

Having determined the change in the area occupied by a biome, a species-area relationship was used to estimate the number of species present in a patch of a given biome and a given size. If there is a decline in the total area with change, the relationship would predict a loss of species within that patch. In this case, a continental z-value (species-area exponent) of 0.15 was used. Biome changes were simulated using a GVM driven by a GCM climate.

All models showed declines in the area of potential distribution of tundra, tundra/taiga and arid lands, and increases in temperate mixed forest, tropical broadleaf forest and grassland.

Under the first scenario with perfect migration, all models showed declines in the areas of tundra and tundra/taiga, respectively ranging between 41–67% and 33–89% of the total area depending on the particular combination of GCM and GVM. Corresponding estimates of species loss were between 8–15% and 6–28% of the biota using a conservative species-area exponent (0.15). Evidence of net declines in arid lands was also obtained. By contrast, temperate mixed forest showed consistent increases (49% on average) and tropical broadleaf forest and grassland also tended to show increases in area.

Under the second scenario with no migration, all biome types declined in area, especially those at high latitudes and altitudes such as tundra, tundra/taiga, boreal conifer forest and temperate evergreen forest (55, 85, 46, 52% loss, respectively). Even tropical broadleaf forest showed an 8% loss in area, corresponding to the possible loss of tens of thousands of species. Although this second scenario is unrealistic in that it assumes zero migration, it does highlight the potential for impacts in a diverse array of ecosystems, and the potential importance of migration in mitigating these impacts.

In order for the biome to successfully move to its new geographical niche, species would be required to migrate at least from the nearest point of the existing biome to each part of the new biome. This assumes that species occupy the whole of their biome space, which is more likely for widespread species. On average, the models showed that species in 19% of global grid cells would require a migration rate of over 1 km/year (the post-glacial rate of movement) to reach new suitable areas (Figure 1). The largest spatial shifts are seen in the northern hemisphere. At 1 km/year, *Picea* (spruce) would require 1,000 years rather than 100 years of migration to keep up with the shifting boreal biome.

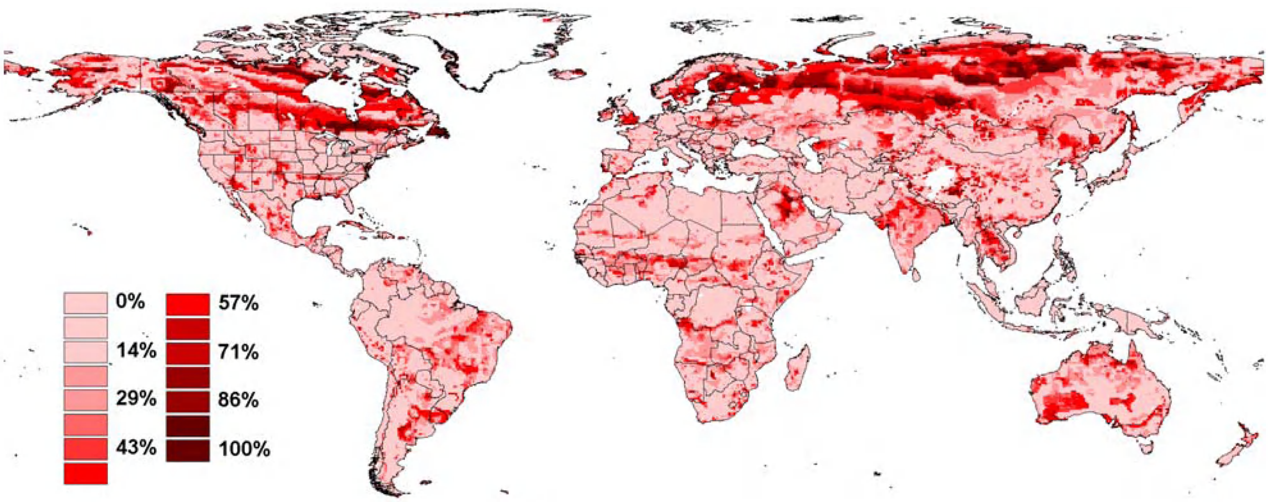

Figure 1. *The proportion of 14 models of biome shifts in response to 21st century climate change in which biome boundaries would have to move at rates in excess of 1 km per year in order to keep pace with the movement of their climate space.*

Hotspots, under Myers' definition, occupy <2% of land area but hold 44% of plant and 35% of vertebrate species. When hotspot areas alone are considered, the range of response to the different scenarios is emphasised. Even when broader biome definitions are adopted, so increasing the modelled habitat breadth of individual species, potential for species loss is high.

With narrow habitat breadth and low migration, the rates of species loss in the model approach those seen with tropical deforestation.

Tree/grass dynamics in a changing world

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In southern Africa, fire-maintained systems have high biodiversity compared to the forest systems that appear with fire suppression. These C4 tropical grasslands and savannas appeared abruptly, between six and seven million years ago. Fire dynamics may have enabled their displacement of the early Tertiary's tall forests.

Fire can be considered a generalist herbivore, which grasslands are able to regenerate from quickly. Young trees do not survive fire well, so savanna trees have fire-tolerant strategies. The sapling accumulates energy reserves at low height, and then shoots up rapidly to place its growing point above fire level. Saplings can be restricted to the understorey for decades.

The Sheffield dynamic global vegetation model (http://www.nbi.ac.za/research/co2.htm) includes a basic fire model, which performs well when compared with long-term burning experiments. When fire is switched off in the DGVM (Dynamic Global Vegetation Model), more forests are seen worldwide, in particular in Africa.

After a fire, high levels of light, water and nutrients are available. CO_2 is then a limiting factor for woody plant growth. With increasing atmospheric CO_2 levels, woody plants reach fireproof height more rapidly. Changes in CO_2 concentration may therefore influence the savanna system, even before potential climate change impacts are considered. Atmospheric CO_2 has rarely been higher than 280 ppm in the last 500,000 years, but post-industrial levels are 370 ppm and rising.

A demographic model of tree response to burning was coupled to the DGVM. Tree numbers increased with CO_2 concentration. They were eliminated from savanna regions in the last glacial period, at low CO_2 concentrations. Some existed in the pre-industrial period, but more occurred under present-day conditions.

These results match palynological records from the Wonderkrater savanna region – little tree pollen existed pre-Holocene here. Savanna appears to be an interglacial phenomenon in South Africa. Savanna tree trials in CO_2 chambers at the National Botanical Institute also match the simulations, although growth rates at 550 ppm are not as high as seen in the physiological model.

Long-term plots were set up in the Kruger National Park in 1954. More saplings have reached maturity in the last 20 years than previously. Worldwide, an increasing tree density is being seen in savannas, and CO_2 concentrations are 20% higher than in the 1950s.

In South Africa, savanna ecosystems host the most species richness and endemic species. A great change in grassland biota will be expected if this level of bush encroachment into fire-dependent systems continues.

Fire policy here is contentious. Anthropogenic fires are still frequent, but are never started deliberately by managers. However, natural burns (caused by lightning) have been enabled to cross roads in order to reach fragmented parts of the savanna. However, a high-CO_2 world is not a 'natural world'.

Two options are to manage for landscape heterogeneity, using patch mosaic burns, or to use frequent intense burns over broader areas to maintain mesic savanna vegetation in its current state. The effects of frequent burning on other savanna species such as invertebrates are not known.

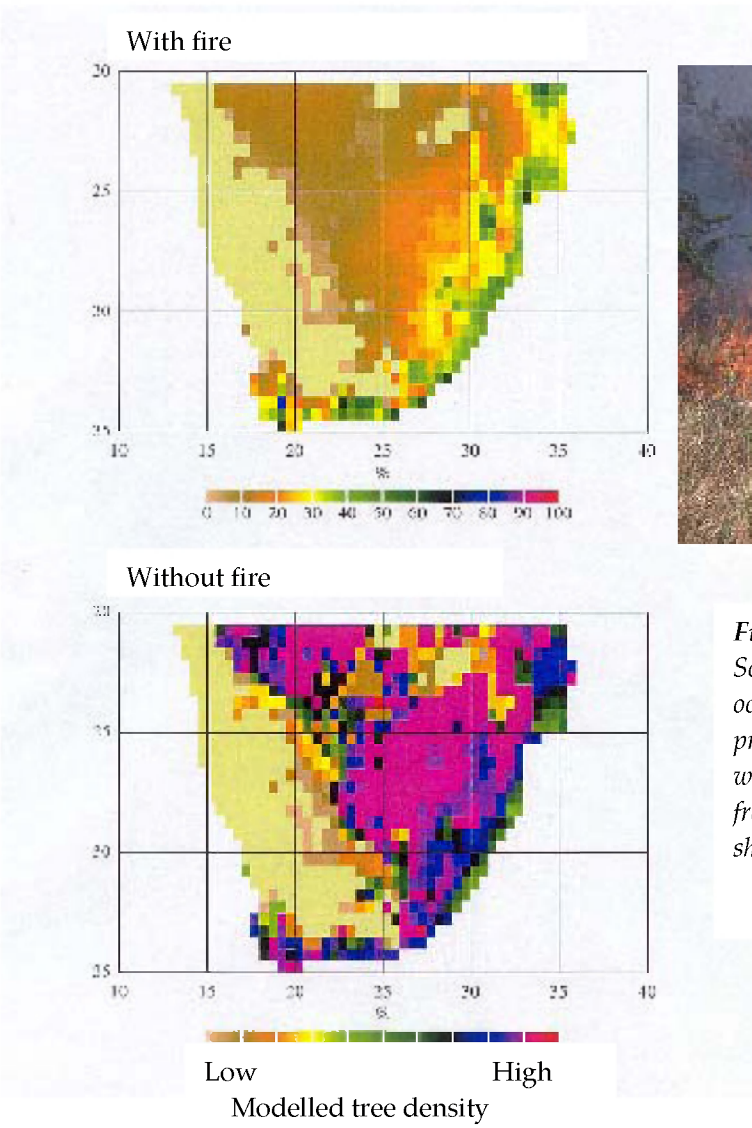

Figure 1. DGVM simulation of the current tree cover in Southern Africa with (top left) and without (bottom) the occurrence of fire. The model indicates that the present preponderance of savanna woodlands and grasslands would probably be replaced by denser forests if fire frequency was much reduced or fire tolerance of trees and shrubs increased.

Climate change and biodiversity in tropical East Asian forests

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Tropical East Asia supports 20–25% of global biodiversity and half a billion people. Until recently, the entire region was forested and plant and animal distributions largely reflected horizontal gradients in rainfall seasonality and a vertical gradient in temperature, both modified by edaphic and topographic factors, particularly towards their drier and colder ends. A latitudinal temperature gradient becomes increasingly important north of 18°N. Plant distributions probably also partly reflect dispersal history.

The limited ability of current climate models to predict inter-annual (and inter-decadal) variability in rainfall patterns and the lack of information on current species-environment relationships makes it difficult to predict impacts of rapid climate change on biodiversity. The most likely direct impact will be the loss of montane endemics because of exceeded temperature tolerances, reduced cloud water and the upward migration of pioneer species. In contrast, the direct impact of changes in rainfall patterns will probably be partly mitigated by adaptations to a rainfall regime that, even in 'normal' times, shows an exceptional degree of variability on all timescales. The direct impacts of climate change on biodiversity will probably be dwarfed by interactions with other human impacts. Tropical East Asia has the highest rates of deforestation, forest degradation and logging in the tropics, and the remaining forest is almost everywhere fragmented and disturbed. Any increase in the frequency and/or intensity of dry periods would accelerate the existing synergy between logging, drought, agricultural clearance and devastating fires.

In the longer term, outlying populations of wet forest species in dry areas, and *vice versa*, on edaphically or topographically extreme sites, will reduce the migration distances needed for equilibration, but fragmentation and the local extinction of dispersal agents will make migration impossible for most species. The evidence for migration deficits in current plant distributions suggests that migration rates for some species will be very slow even where continuous habitat is available. The impacts of climate change on regional biodiversity can be mitigated only by the protection of large tracts of minimally disturbed forest that are continuous over both altitudinal and rainfall gradients. Existing protected areas are insufficient, so this will require both the rehabilitation of damaged forests and the reforestation of degraded areas. Planning at the regional scale needs to start now.

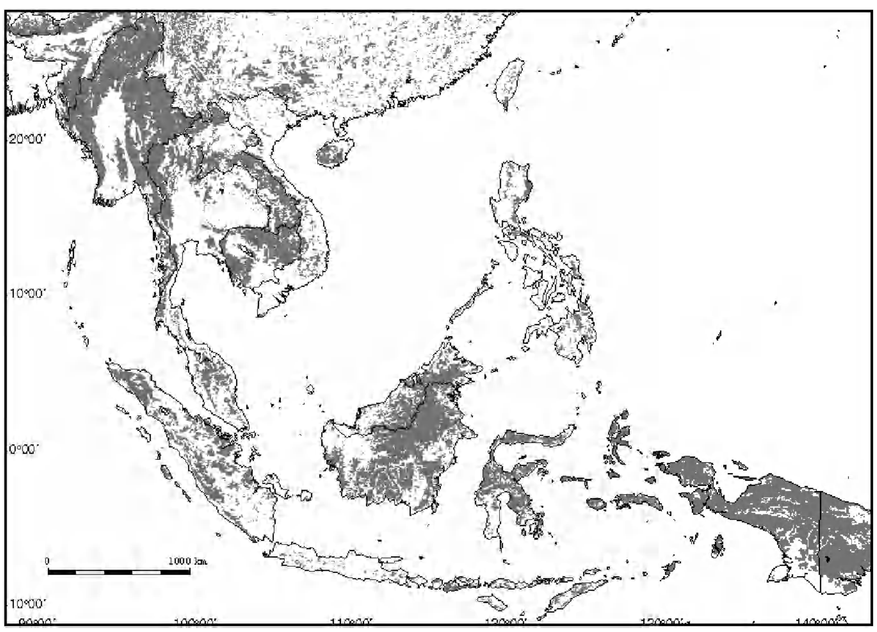

Figure 1. *Forest cover (shading) of tropical East Asia in about 1997 showing the fragmentation of what would originally have been a largely forested landscape. Map from UNEP-WCMC.*

Climate change and Amazonian forest biodiversity

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This thesis can be accessed from http://www.geog.leeds.ac.uk/projects/l.miles/

Species' ranges are configured according to their tolerance of environmental conditions, especially climate, and their history of dispersal since speciation. Previous studies of the potential impact of climate change on biodiversity have been biased towards species of high latitudes. This situation results from a lack of detailed knowledge about the distribution of tropical biodiversity, and from the smaller degree of warming expected at low latitudes. However, various General Circulation Models (GCMs) simulate regional drying and increasing seasonality for parts of the tropics, including Amazonia. This may have a greater impact on tropical forest flora than temperature change alone. The Amazon region holds a high proportion of global biodiversity, yet conservation plans rarely consider possible climate change impacts. An iterative selection routine was carried out to include species to represent the greatest practical range of Amazonian plant diversity, from the families *Arecaceae*, *Balanophoraceae*, *Bignoniaceae*, *Caryocaraceae*, *Chrysobalanaceae*, *Fabaceae*, *Lauraceae*, *Proteaceae*, *Rubiaceae* and *Sapotaceae*. Species were classified into plant functional types (PFTs), which share traits such as growth form and reproductive strategy. These species' ranges were projected from available spatial data and their response to climate change scenarios estimated.

Species' current distributions were modelled over a coarse scale (a 1° latitude-longitude grid), using a suitability index based on bioclimate variables. Distributions were additionally limited by species' absolute tolerances to extreme values, and by dispersal barriers. A size-structured population was simulated for each cell, to enable modelling of lags in response to climate change.

In the standard impact scenario (SIS), future population processes were simulated over 100 years, with changes in the variables governing cell suitability being applied annually according to anomalies from a selected GCM. In a reduced impact scenario (RIS), the run was repeated for each species using anomalies of half that magnitude. The range of potential outcomes for each species and PFT was evaluated. Widespread impacts were seen under both scenarios. An alternative impact scenario (AIS) was devised to examine the effects of allowing some competitive 'c-species' to thrive under heightened actual evapotranspiration (AET; see Figure 1). The most vulnerable taxonomic groups, PFTs and geographical regions were identified as targets for monitoring and conservation action. In particular, there is a dramatic loss of species' viability in much of northeastern Amazonia at 2095 under all scenarios. The far western part of Amazonia is identified as important for persistence of the greatest number of species. Areas falling between the major rivers of the region have very limited distribution data, so are highlighted for future biodiversity survey work.

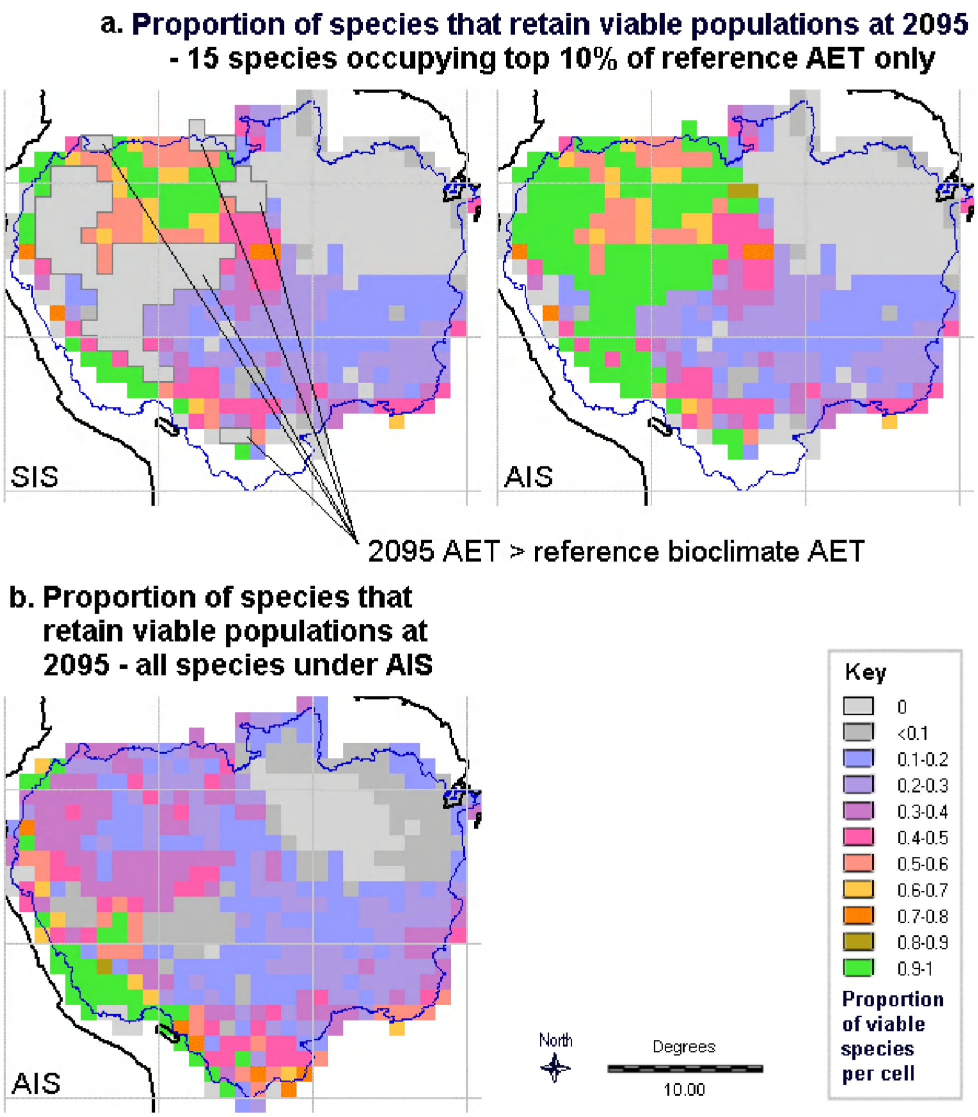

Figure 1. Proportions of species that are expected from models to still have viable populations in different parts of Amazonia in 2095 under future climate scenarios. (a) The proportion of 15 selected species expected to retain viable populations at 2095 for a standard climate change scenario (SIS) and for an alternative scenario (AIS) in which there are competitive species (see text). Selected species occur in the top 10% of actual evapotranspiration (AET) values under the present climate. (b) Proportion of all 69 species in the study that retain viable populations at 2095 under the alternative impact scenario (AIS).

Climate change, ocean processes and plankton regime shifts

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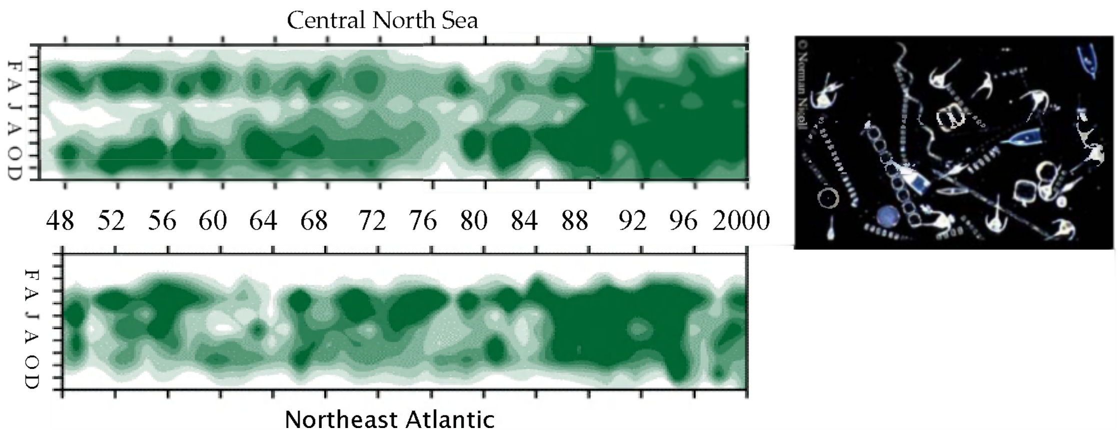
The third report of the Intergovernmental Panel on Climate Change (IPCC) has shown that the rapid rise in mean global temperature seen in the last century was exceptional in the context of the last millennium. Mean surface (land and sea) global temperatures increased by 0.6°C ± 0.2°C in the 20th century and the heat content of the oceans, integrated to 3 km depth, has increased since 1950. There is now a scientific consensus that these increases are attributable to the even greater rate of increase seen in greenhouse gases. Surface temperatures are expected to increase by a further 1.4 to 5.8°C by 2100. It is likely that changes in temperature at this scale and rate will have a pronounced effect on northern latitudes in the Arctic and, in turn, on the thermohaline circulation of the North Atlantic, which plays such a key role in the 'Global Conveyor Belt'. We may already be seeing evidence of these effects as the sea surface temperatures of the eastern Atlantic are highly correlated with northern hemisphere temperatures over the last 40 years.

In the eastern Atlantic, evidence from the Continuous Plankton Recorder (CPR) survey indicates that plankton are able to integrate climatic signals that may not be the main forcing variable; as such, plankton may be used as an index of climate change. Strong links have been demonstrated between the plankton and both Northern Hemisphere temperature (NHT) and the North Atlantic Oscillation (NAO), the dominant mode of atmospheric variability in the North Atlantic. The colour index of the CPR survey has shown a substantial increase in season length and intensity (Figure 1) and implies increases in chlorophyll and primary production in a wide belt across the North Atlantic and especially in shelf seas. Parallel increases in the benthos imply that sedimentation from the plankton has also increased in the last decade. At approximately the same time in the mid 1980s there appears to have been a step-wise change in physical, chemical and biological characteristics (at all trophic levels) in the North Sea that has been termed a regime shift. This is borne out by cluster analysis, which groups years according to both physical (sea surface temperature and NAO) and biological (phytoplankton, zooplankton and salmon catches) characters. This shows a distinct change from 1987 onwards. Changes in biogeographic zones and in the biodiversity of the plankton are linked to the decadal changes seen in plankton abundance with evidence for a northerly movement of warmer water plankton on the eastern side of the Atlantic and a southerly movement of plankton associated with colder water in the western Atlantic.

While climate variation may be considered to be natural, both the observed and predicted rates of climate change are unusually rapid and human effects on climate now appear to override natural variability. Ocean circulation and temperatures are changing in response. Physical and biological responses by oceans can be rapid and changes can be step-wise in the form of regime shifts. The northeast Atlantic may see large amplitude changes in the future.

Figure 1. *Changes in phytoplankton biomass and seasonality in the North Sea and northeast Atlantic as part of a regime shift in associated physical and biological parameters that began in 1987. The left hand pair of diagrams shows phytoplankton biomass (intensity of shading) in relation to month (y-axis) and calendar year (x-axis). An increase in biomass after 1987 is apparent in both the North Sea (upper) and northeast Atlantic (lower).*



Climate change and fisheries

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Fisheries are the major cause of mortality for marine fish, once they have reached a catchable size. Most fish stocks have been declining for some time due to fishing. Nonetheless, climate fluctuations are also known to cause extensive shifts in species distribution and local biodiversity. Furthermore, climate change and fishing pressures may interact to exacerbate the risk of collapse of fish populations to below the level at which they can support fisheries.

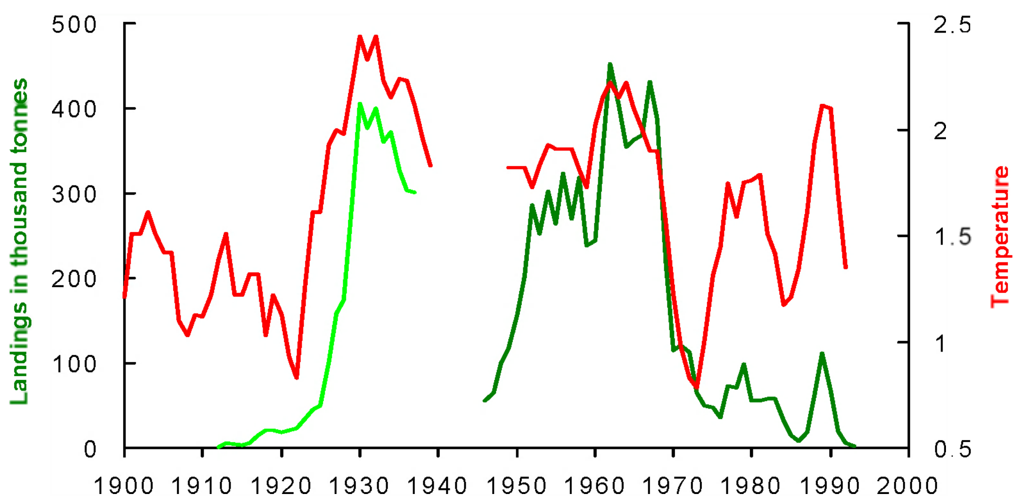
The demography of marine fish tends to differ from that of terrestrial vertebrates and freshwater fish in several important respects. Marine fish have large population sizes with fewer boundaries to migration, high fecundity once mature, often have a dispersive plankton stage and they undergo large population fluctuations. There appear to be fewer barriers to migration in the sea. Hence, the constraints on distribution shifts in the sea are very different (and probably fewer) than on land or in freshwater systems, and marine populations probably maintain greater genetic exchange. Nevertheless, there is also concern about possible loss of genetic diversity (at least of genotypes), which may in turn reduce the capacity to adapt to climate change.

Fisheries' catch information provides much of our knowledge about fish populations. These data provide evidence for associations between climate change and marine fish abundance and distribution. The annual landings of cod in Greenland have varied enormously over the 20th century, ranging from very small local catches to almost 500,000 tonnes. This shows a close correlation with sea temperature fluctuations between 1 and 2.5°C, warmer temperatures being associated with bigger catches, but catches since the early 1970s have been lower than expected from temperature alone (Figure 1). Changes in the abundance and distribution of other fish species in west Greenland are also associated with the period of warming from the 1920s. New species appeared from 1920 (*Melanogrammus aeglefinus, Brosme brosme,* *Molva molva)*, rare species became common and extended their ranges (*Pollachis virens*, *Salmo salar, Squalus acanthias)* and Arctic species no longer occurred in southern areas, but shifted their range northwards (*Mallotius villosus, Gadus ogac, Reinhardtius hippoglossoides).* Thus, climate can cause extensive shifts in species distribution and in local biodiversity.

In the North Sea, fishing has reduced life expectancy of several species, most notably plaice and sole, from around 10 years to two and cod, haddock and whiting from about four years to one year or less. Fishing tends to selectively remove large individuals and species. The Scottish August Groundfish Survey has shown that maximum fish size in the North Sea has declined by a factor of nearly eight between 1920 and 2000. The southern North Sea is at the edge of the cod's southern climatic range and the combination of warming and overfishing has led to a dramatic reduction in numbers. Cod spawning biomass in the North Sea is at a historic low, but Barents Sea populations are still strong.

Climate change and fisheries can impact on biodiversity is several ways. At the most obvious level, they can cause species extinction. They can cause stock extinction, which may or may not entail the loss of alleles or genotypes, and adverse changes in genotypic frequency. They can change distribution and abundance and we have most evidence for this. Climate change and sea level rise effects are probably severe for some sensitive systems, such as coral reefs and mangroves, and these will also affect fish populations. It is also becoming clear that the North Atlantic Oscillation has a strong, but not necessarily simple, effect on phytoplankton, zooplankton and fish dynamics.

Figure 1. *Landings of cod (green lines) and sea temperatures (red lines) at Greenland during the 20th century. Several large changes in cod landings coincide with changes in sea temperature. However, since the early 1970s, cod landings have been low relative to expectations from sea temperature.*



Climate change and the Antarctic marine ecosystem

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The Antarctic climate has changed throughout time and on a wide range of temporal scales. Southern Ocean bottom temperatures have changed dramatically over the past 60 Ma, as has been demonstrated by palaeotemperature studies of benthic foraminifera isolated from deep-sea sediment cores. Glaciation of the Antarctic continent probably began 36–40 Ma BP, and throughout its existence the continental ice-cap has varied in volume and the extent to which it has covered the continental shelves. A key driver of this variability has been Milankovitch cyclicity, long-term variations in the Earth's orbit which affect received solar radiation on timescales ranging from <20,000 to >100,000 years. These variations affect the timing and duration of seasons, and the extent of the tropical and polar regions. For the last 15 Ma there has been consistent cooling of the Southern Ocean, and this is the period that has driven the evolution of the Antarctic climate and biota we observe today.

Climatic and tectonic changes on geological and Milankovitch scales have produced a generally rich and diverse Antarctic marine fauna adapted to cope with this variability, by slow growth, longevity and intermittent recruitment. The marine fauna of Antarctica is generally rich and diverse, though some taxa are more speciose than others (notably species-rich groups include amphipod and isopod crustaceans, echinoderms and pycnogonids). In contrast, the Southern Ocean has very few decapod crustaceans, and is dominated by only one group of teleost fish. Climate change is likely to influence this biodiversity through three processes, namely direct temperature effects on organisms, oceanographic shifts and changes in the dynamics of sea-ice. In some cases, any effects may be exacerbated by changes in UV flux as a result of changes in the seasonal development of the ozone hole. At present, there is evidence for small temperature changes in both shallow and deep waters around Antarctica, and for some associated oceanographic changes. There is also some evidence for changes in sea-ice distribution and dynamics, though here it is difficult to distinguish a climate-change signal from natural long-period variability in the system. The clearest evidence for long-term changes in sea-ice dynamics comes from the Amundsen and Bellingshausen Seas, where there has been a decrease in winter sea-ice cover of about 10% since satellite records began. The atmospheric climate of the Antarctic Peninsula is warming faster than almost anywhere else on the planet, with warming being most evident in winter, and this may be related to the changes in sea-ice dynamics observed in the Amundsen and Bellingshausen Seas. In contrast, the climate of the Antarctic continent shows no consistent pattern, and some places have even displayed a slight cooling.

Data for biological responses to climate change in Antarctica are few, although there are strong indications of changes in population dynamics of some seabirds in relation to sea-ice. Climate change has already affected the breeding distribution of pygoscelid penguins, but no change has yet been observed for plankton or benthos. Some marine invertebrates have been shown to live near their maximum temperature limits (a situation analogous to that of some tropical corals) and would therefore seem liable to extinction should seawater temperatures rise significantly in the near future. How the fate of individual sensitive species relates to the response of whole ecological assemblages is, however, far from clear.

The dynamics of sea-ice are complex, and can influence the population dynamics of many zooplankton which depend on sea-ice at stages in their life-cycle. An excellent example of this is the Antarctic krill, *Euphausia superba*, which is widely regarded as a keystone species in the food web at lower latitudes in the Southern Ocean. Young krill hatch along the western Antarctic Peninsula and are carried in the strong Antarctic Circumpolar Current to South Georgia, where they form a major part of the diet of many higher predators (fish, squid, seabirds and marine mammals). This means that variations in krill supply driven by changes in sea-ice dynamics thus influence the breeding success of dependent predators at South Georgia.

Demonstrating long-term changes in the biodiversity of marine systems is hindered by the paucity of data and the overwhelming effects of man's activities, even in Antarctica. Important insights into the potential effects of future climate change come from examining historical changes in the fauna, and from comparison of the two polar regions. To understand the impact of climate change on the Antarctic ecosystem as a whole, one needs to understand the structure of the food web. Although often portrayed as a simple, two-step linear food chain (diatoms to krill to whales, the classic Antarctic food chain of many textbooks), the Southern Ocean food web is similar to other marine food webs in that it is non-linear, incorporates a microbial loop and has a significant flux to benthos. The major difference from non-polar food webs is the role of sea-ice. The food web structure and its non-linear dynamics make prediction of future responses very difficult. The removal of great whales might have resulted in a regime shift to a system dominated by fur seals and squid. Currently, we cannot predict the biological consequences of climate change on the Antarctic. Rather than focusing on individual taxa, the impact of climate change on assemblages needs to be investigated.

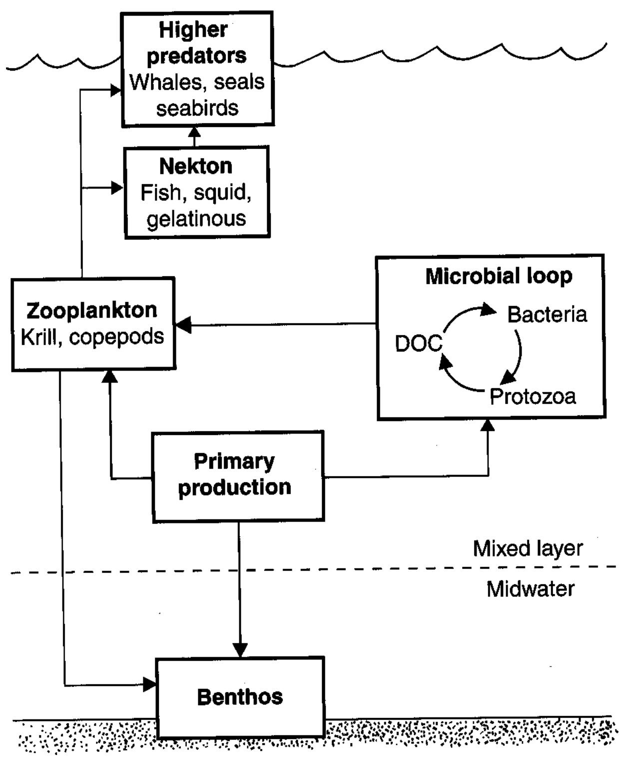

Figure 1. Schematic diagram of the Southern Ocean food web.

The McMurdo Dry Valleys, East Antarctica: terrestrial ecosystem responding to changing climate

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The global mean surface air temperature has increased by 0.19°C per decade from 1979 to 1998. Despite climate model predictions that show greenhouse gases will cause amplified warming in polar regions, clear signs of warming in Antarctica over the closing half of the 20th century have been confined to the Peninsula region. Ecological impacts on the Antarctic Peninsula have been attributed to this regional warming.

In contrast, there is evidence of an annual cooling of 0.7°C per decade in the McMurdo Dry Valleys (77–78°S, 160–164°E) between 1986 and 2000. Fall and summer cooling of 2.0°C and 1.2°C per decade, respectively, dominate this trend. Analysis of Antarctic surface data from 1966 to 2000 suggests that cooling has been a dominant feature of Antarctic climate, outside of the Peninsula. Cooling in the dry valleys was significantly related to decreased winds, and accompanied by increased clear-sky conditions. One consequence has been increased thickness of lake-ice. Ecosystem response to the cooling in the dry valleys was remarkably rapid and included decreased lake primary productivity (6–9%/year) and soil invertebrate numbers, especially soil nematodes (>10%/year; Figure 1).

Despite these rapid responses to recent climate change, there is evidence that the characteristic biota of the dry valleys' ecosystem has persisted over very long timescales. There is evidence that past temperatures have been considerably cooler than at present so the system is likely to be resilient if current changes continue in the medium term. One clear consequence of warming and cooling is a shift between a soil-dominant ecosystem and a lake-dominant ecosystem. During warm periods, lake levels rise and consume habitat for the soil organisms. Likewise, during cold periods, lakes dry up and soil habitat area increases. The actual response of the ecosystem to these changes has been the focus of research for the McMurdo Dry Valley Long Term Ecological Research (LTER) group since 1993. In addition to ongoing monitoring and experimental programs, the LTER recently (November 2002) extracted long (up to 10 metres) sediment cores from the dry valley lakes so that direct evidence of how the lake ecosystems respond to changing climate will be available, allowing us to better predict response to future climate change.

This contribution is based on: P. T. Doran, J. C. Priscu, W. B. Lyons, J. E. Walsh, A. G. Fountain, D. M. McKnight, D. L. Moorhead, R. A. Virginia, D. H. Wall, G. D. Clow, C. H. Fritsen, C. P. McKay, and A. N. Parsons, 2002. Antarctic climate cooling and terrestrial ecosystem response. *Nature* 415: 517–520.

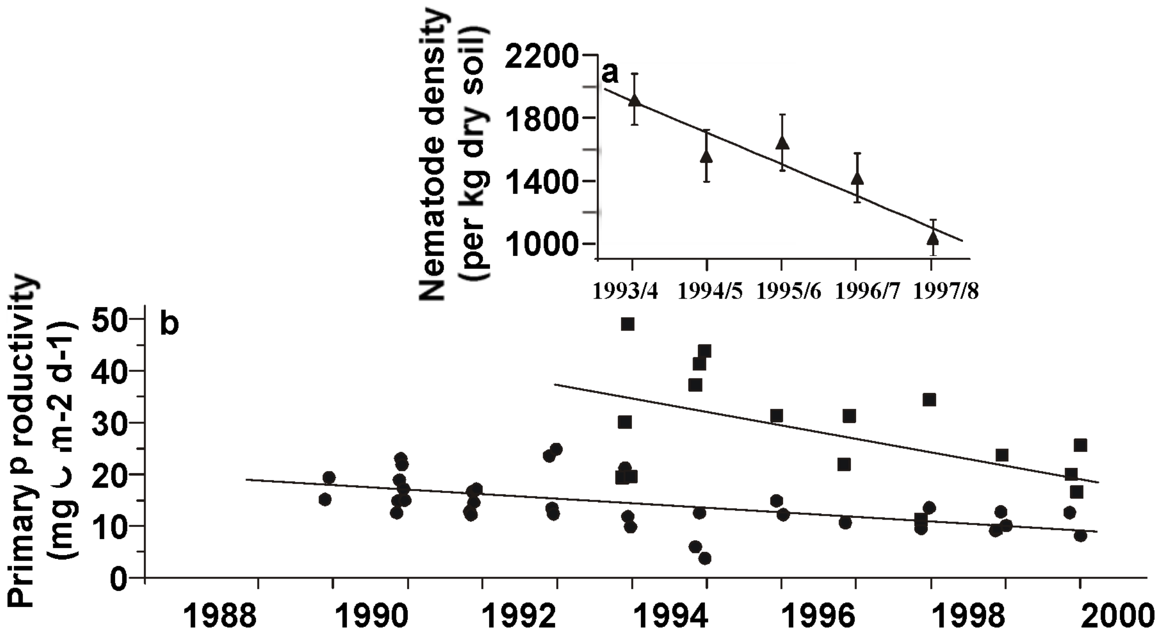

Figure 1: ***a.*** *Total number of soil nematodes over time in experimental plots on the south shore of Lake Hoare* ***b.*** *Depth integrated primary productivity during November and December in east (circles and lower trend line) and west (squares and upper trend line) lobes of Lake Bonney (modified from Doran et al. 2002).*

Effects of climate change on Arctic vegetation

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As part of global climate change, temperatures are predicted to increase by 2–6°C in Arctic latitudes by the end of the century, accompanied by an increase in precipitation, both changes being greatest in the winter months. Investigations of the history of vegetation in the Arctic demonstrate that when, during the Tertiary, the Earth was warmer than in the recent past, trees grew successfully at very high latitudes. Even during the past 10,000 years, the Arctic tree line was displaced substantially northwards during the early Holocene relative to its present position; temperatures at that time are estimated to have been c. 2°C warmer than in the recent past. At this time, the global extent of tundra was probably about 20% less than at present. About 5,000 years ago, birch and pine woodland extended to the northern coast of Finnmark. The tree line retreated south about 2,000 years ago.

The position of the Arctic tree line is of key importance, not only to other elements of the Arctic vegetation, but also to other organisms that are associated with the tundra biome that lies poleward of the tree line. Considerable changes to the abundance and distribution of tundra-adapted organisms would be expected if, as expected, global climate change leads to a reduction of the global extent of tundra by 50%. In addition, shifts of the tree line generate strong positive feedbacks to the climate system, especially via negative effects of tree cover on albedo that causes further warming and extension of suitable climate conditions for trees.

Field experiments in the Arctic indicate that the tree line may be inherently rather stable and resilient to relatively small fluctuations in climate, principally as a result of stabilising feedbacks at landscape scales. This leads us to expect a non-linear response when climatic change exceeds an as yet unpredictable threshold beyond which these stabilising feedbacks break down and positive feedbacks take over. A field experiment in which dead birch trees were erected on tundra as an artificial forest showed that this led to earlier bud burst of planted birch saplings within the forest and earlier snow melt (Figure 1). Propagules of trees are already dispersed widely beyond the tree line, so migration rates are unlikely to much delay the spread of forests. Browsing by mammalian herbivores is also unlikely to have much impact, at least for birch, though pine and larch seedlings are selectively eaten by lemmings and voles. The change in feedback mechanisms will lead to a rapid shift to a new stable state in which the extent of tundra is markedly reduced and resultant positive feedbacks will lead to strengthened polar warming. Although the threshold for this effect is unknown, it is considered likely to be within about 2°C warming compared with the present.

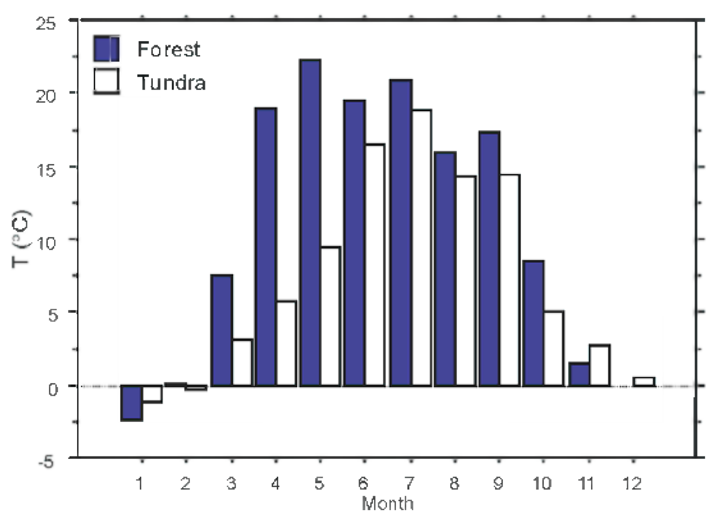

Figure 1. *Maximum monthly temperatures were much higher in spring within an artificial forest made from dead birch trees than on adjacent tundra.*

Biodiversity and climate change in the tropical montane rainforests of northern Australia

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The Australian Wet Tropics World Heritage Area is the most biologically rich area in Australia. Although it only covers 10,000 km^2 (= 0.1% of Australia) in northern Queensland, over 600 vertebrate species occur there – of which 83 species are regional endemics. Of these, 72 species are restricted to the rainforest.

The endemic fauna of this area is particularly vulnerable to climate change due to a) its biogeographic history, having been restricted and therefore adapted to cool, wet and relatively aseasonal upland environments during past glaciations (c. 18,000 years BP) and b) the altitudinal gradient, ie species are adapted to a particular altitudinal niche and impacts of increasing temperatures are predicted to be most severe across altitudinal gradients. Altitude is the most important macroecological gradient, affecting almost every process. Bird species richness peaks at mid altitudes (c. 600–800 m).

The effects of increases in temperature of between 1°C and 7°C on species distribution were assessed using bioclimatic modelling, based on a database of over 220,000 records from field samples and point locations. Vertebrate distributions were modelled in relation to measures of temperature, rainfall and radiation using the bioclimate model BIOCLIM. Estimates were then made of the change in core range of each species under different climate scenarios, assuming that species continue to occupy the climate space they currently use. Models for 62 species of montane (>600 m altitude) endemics indicate that 1°C warming will result in an average 40% loss of potential core range, 3.5°C warming a 90% loss and 5°C warming a 97% loss. Warming of 7°C results in the loss of all potential core range for all species. About half of the montane endemics would lose all of their core potential range with 3.5°C warming. Genetic diversity and evolutionary potential might also be lost, because there is considerable genetic diversity linked to the distribution of glacial refugia. Some of these refugia would cease to have suitable climate with even moderate warming.

Insect and bird species richness and abundance are lower in areas with the greatest seasonality. Expected changes in seasonality include increased length of dry seasons, reduced climatic predictability and decreased moisture input. These are likely to affect insect biomass and, therefore, resources for insectivorous birds.

The physiology of many animals is not adapted to warmer temperatures. Some arboreal possums, highly adapted and poor dispersers, are prone to die of overheating and the eggs of microhylid frogs desiccate.

Climate change is likely to cause catastrophic extinctions in the montane wet tropics due to range restrictions, increased fragmentation and physiological stress, resulting in large changes to community structure.

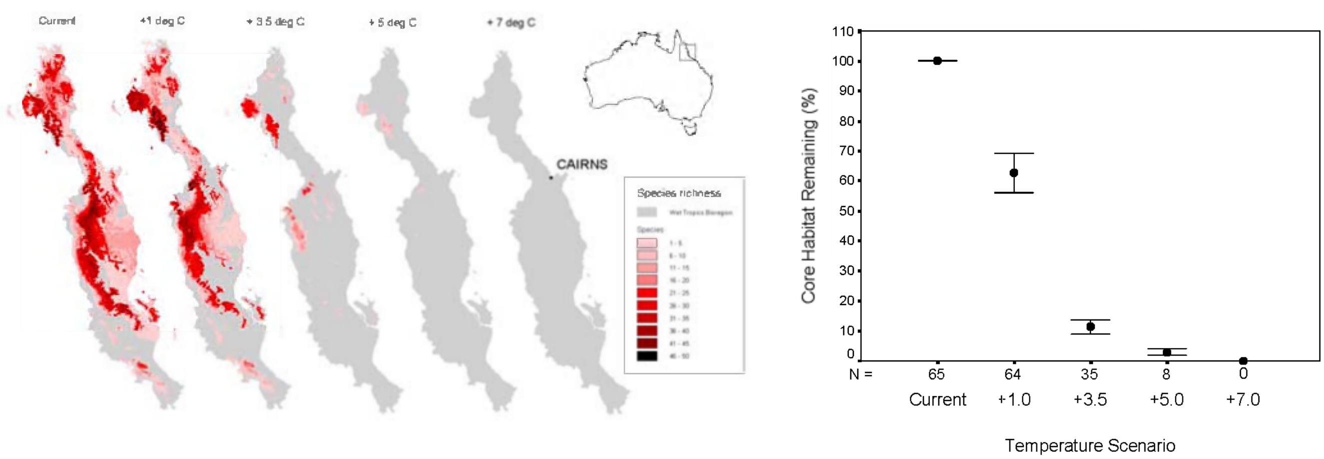

Figure 1*. Species richness of endemic montane vertebrates in northern Queensland wet tropics (left). Maps show the current species richness estimated from bioclimate models (far left) and expected future species richness of these endemics if they shift their ranges to remain in the same climate space under different scenarios for future warming. The graph on the right shows the mean proportion of the core habitat remaining for 62 montane endemic vertebrates according to these models in relation to the level of warming.*

Climate change and habitat fragmentation

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In post-glacial times, it is known that some species changed their distributions rapidly in response to climatic amelioration, but they did not have to do so across landscapes dominated by human activities. This paper discusses how habitat fragmentation may impede the ability of species to track contemporary climate change in regions where the climate is becoming more favourable for certain species, and how climate change may exacerbate the effects of habitat fragmentation.

Species show variable levels of success in shifting their ranges through fragmented landscapes in response to climate change. Whilst mobile generalists may increase their ranges, species with low dispersal rates, including sedentary habitat specialists, may not be able to track climate change. Recent studies of British butterfly species illustrate these trends. Within a group of species which should all be increasing their ranges in Britain if they were fully occupying areas with suitable climate, mobile generalists such as the speckled wood and comma have increased their ranges by 24% and 30% respectively in recent years, whilst the silver-studded blue (a sedentary specialist) has declined by 28%. Habitat fragmentation reduces dispersal ability and contributes to lags in distributional change.

The rate and direction of species dispersal is based on habitat availability (faster through more suitable landscapes), population density and growth, dispersal distances and the location of 'refuges'. Habitat availability changes with climate and the habitat requirements of species change with climate; indeed, some species show changes in habitat requirements to allow dispersal through patchy landscapes. For example, the brown argus has rapidly expanded its range since the early 1990s. It is no longer restricted to calcareous grasslands, where the common rock rose is its host plant, but is now using *Geraniaceae* as its host in many newly-colonised areas.

Distributional expansions are closely linked to habitat availability, and contractions exacerbated by fragmentation. The consequence is that biological communities will become increasingly dominated by certain types of animals and plants; mobile generalists may continue to prosper, whereas specialists are likely to continue to decline under the combined onslaught of habitat loss and climate change.

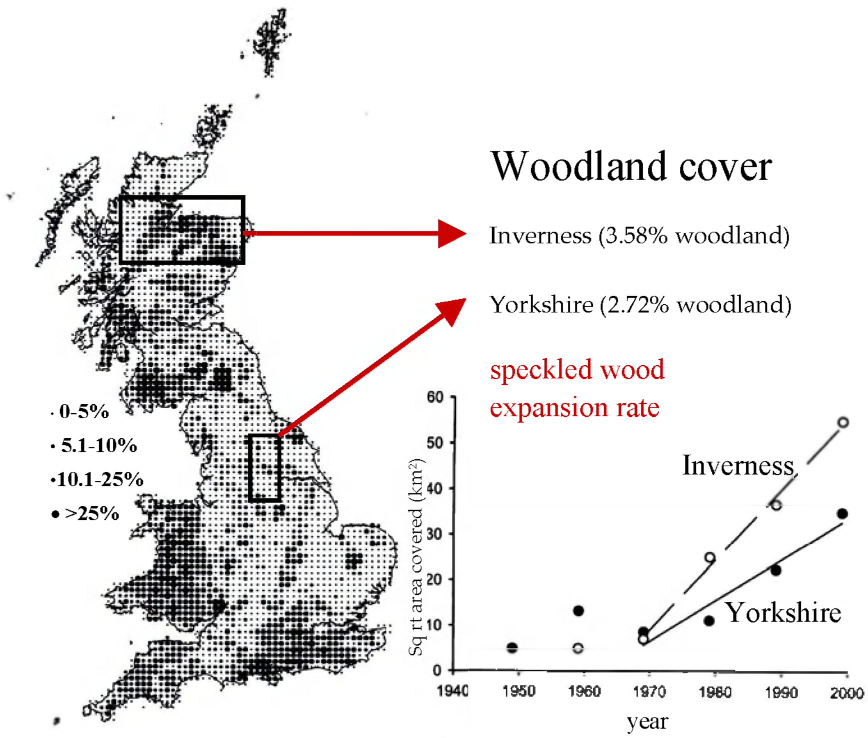

Figure 1. *The rate of spread of speckled wood butterflies Pararge aegeria into areas with newly suitable climate, as identified by bioclimate models. The rate of spread was more rapid where the species' woodland habitat was more extensive.*

Graphs from: Hill, J.K., Collingham, Y.C., Thomas, C.D., Blakeley, D.S., Fox, R., Moss, D., and Huntley, B. (2001). Impacts of landscape structure on butterfly range expansion. *Ecology Letters* 4: 313-321.

Impacts of climate change on managed landscapes

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The Intergovernmental Panel on Climate Change (IPCC, 2001) concluded that 'the collective evidence indicates that there is a *high confidence* that recent regional changes in temperature have already had discernible impacts on many physical and biological systems'. Climate change is an important driving mechanism for altering the distribution of species and, therefore, the species composition of the habitats and ecosystems that characterise landscapes. The majority of European landscapes, however, are managed, often intensively, for a range of socio-economic purposes and are subject to both natural and anthropogenic pressures.

The ACCELERATES project (Assessing Climate Change Effects on Land use and Ecosystems: from Regional Analysis to The European Scale) is funded by the European Commission and is assessing the vulnerability of European agroecosystems to environmental change. This includes modelling the impacts of climate change on agriculture and biodiversity, both across the European Union and in selected habitats in six regions: the Ardennes, Belgium; East Anglia, UK; Northern Jutland, Denmark; Belluno Valley, Italy; Lesvos, Greece and Almeria, Spain.

The MONARCH project (Modelling Natural Resource Responses to Climate Change) is investigating the impacts of climate change on key species and habitats in Britain and Ireland. It has already shown that climate is one of several drivers of change affecting the distribution of species. The models are now being downscaled to provide landscape-scale guidance for setting nature conservation objectives in the context of climate change, and are being tested in four contrasting case study areas in the UK (Hampshire, Central Highlands, Snowdonia and Fermanagh/Tyrone/Donegal) selected for their susceptibility to climate change and conservation importance.

This paper outlines the methodologies being developed in these projects to examine the relationships between the impacts of climate change and land cover change on species and habitats in managed landscapes. Dispersal modelling can simulate distributional changes driven by the ecology of the species and land use and climatic changes. Climate is important in influencing the distribution of species at the macro (European) scale, whereas land cover appears to dominate at the meso (regional) scale (Figure 1). Nature conservation policy needs to adopt a more holistic, dynamic approach to accommodate the changes in the distribution of species and the composition of habitats across landscapes brought about by climate change and other drivers of environmental change.

Further details of this research can be found at:
http://www.geo.ucl.ac.be/accelerates/
http://www.ukcip.org.uk/model_nat_res/model_nat_res.html

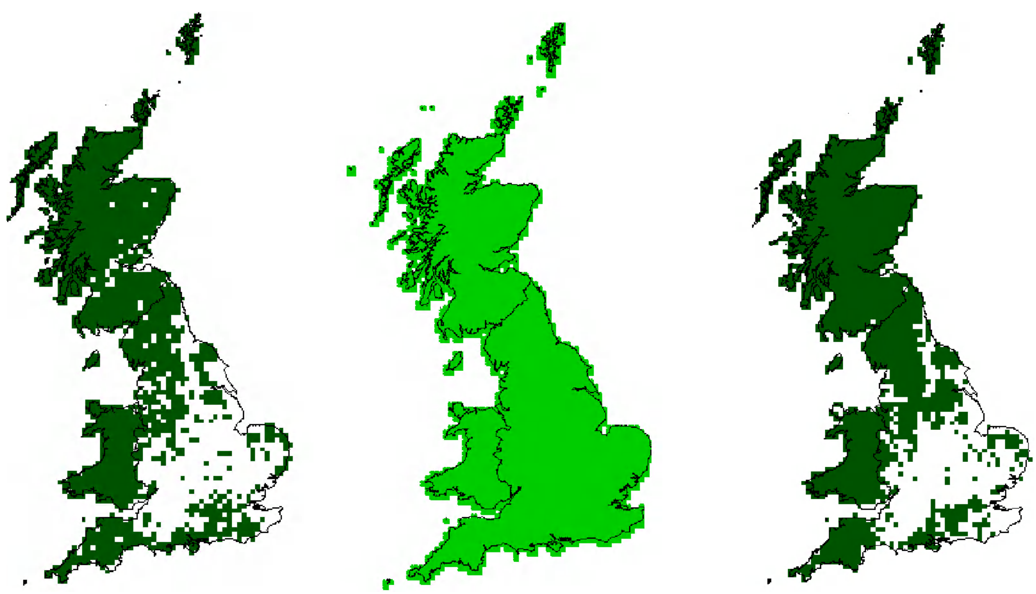

Figure 1. *Observed distribution in Great Britain of the plant Erica tetralix by 10-km squares (left), the distribution of potentially suitable climate according to a bioclimate model based on neural networks (centre) and a simulated distribution from a model that takes both climate and land cover into account (right).*

Hotter and weedier? Effects of climate change on the success of invasive species

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Biological invasions and climate change are two of the greatest environmental challenges that we face today. Individually, each of these elements of global change is the subject of much research. However, studies of invasion biology have rarely considered climate change, and *vice versa*. Such research is important because biological invasions can have strong effects on the structure and function of ecosystems that are responding to a changing climate and on the services provided by those ecosystems; climate change is also altering the context in which potentially invasive species succeed or fail.

There is a variety of reasons why climate change might be expected to increase the success of biological invaders. For instance, a rapidly changing climate might favour species that can extend their ranges quickly or that can tolerate a wide range of climatic conditions. Both of these traits are shared by many invasive plant species. As species shift ranges and habitat compositions change in response to climate change, animals that are generalists may have greater competitive success than specialists. Invasive animal species tend to be generalists, which may increase their success and threaten some native species.

Few studies have focused on the general mechanisms through which climate change could benefit invasive species. However, a number of studies have examined responses of the biota in a specific area to year-to-year differences in environmental conditions, or to experimental manipulations. Results from these studies can help us search for general patterns, and give us some indication of the type of responses that we can expect in the future. For example, the range of invasive species is directly influenced by climate and less by biotic interactions, whilst abundance is indirectly influenced by climate and more by resource availability.

Although few studies have addressed this topic, it is clear that some aspects of climate change will exacerbate problems with some invasive species. How much climate change will benefit invasive species remains difficult to predict and will always be difficult to measure. Hopefully, results from future research will teach us how to minimise the benefits that invasive species might draw from a changing climate.

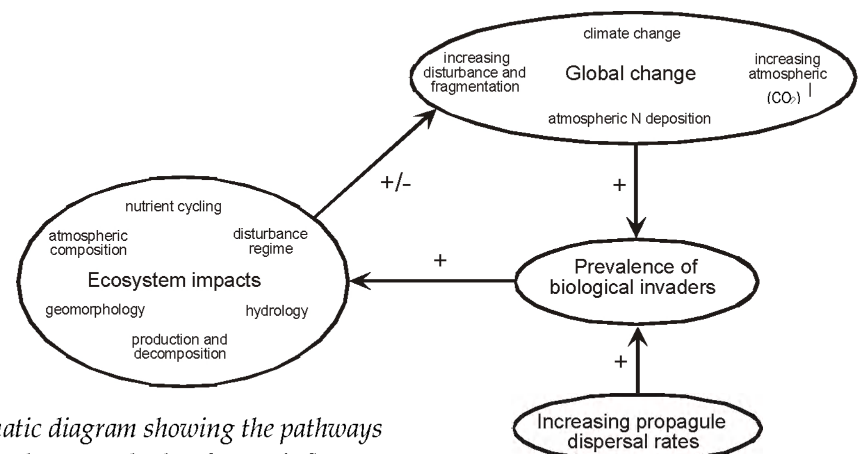

Figure 1. *Schematic diagram showing the pathways by which climate change and other factors influence the impact of invasive species.*

Climate change and sea level rise impacts on mangrove ecosystems

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Mangrove forests are tropical intertidal habitats and are extensively developed on accretionary shorelines. There are 34 species of mangrove trees, in addition to three hybrids, with the centre of diversity being in southern Papua New Guinea. There is a decline in diversity from west to east across the Pacific, reaching a limit at American Samoa, while Atlantic mangrove species diversity is relatively poor. Global distribution is controlled by the 20°C isotherm, with diversity, forest height and associated productivity declining with increasing latitude away from the equator.

Sea level rise poses a major threat to mangrove ecosystems through sediment erosion, inundation stress and increased salinity at landward zones. These problems will be exacerbated for mangrove stands that are subjected to 'coastal squeeze', ie where landward migration is restricted by topography or human developments. Increased air temperatures and atmospheric CO_2 concentrations are also likely to increase mangrove productivity, change phenological patterns, and expand the ranges of mangrove forests into higher latitudes.

Mangroves can provide important services for adjacent ecosystems, and also supply many useful products to human societies. For example, mangroves provide (1) nursery habitats for many species of fish and invertebrates that spend their adult lives on coral reefs, (2) sediment trapping to sustain offshore water quality for coral reefs, (3) protection for inland sites from storm surges and flooding, (4) building materials, (5) traditional medicines, (6) firewood and (7) food. As human populations have expanded, the shortage of productive land in many developing countries has led to the clearance of large areas of mangrove for agriculture and aquaculture production. Demands for timber (for charcoal, building etc) and coastal development space have also been highly damaging. Mangrove forests in some areas have been reduced to mere relicts of their former ranges as a result of human exploitation. In addition to these pressures, mangroves are threatened by sea level rise, projected between 0.9 and 8.8 mm/year. Although there are several factors important in determining patterns of mangrove advance or retreat, studies have shown that mangroves are closely controlled by sea level elevation at their seaward margin.

Mangrove species display a distinct zonation from low to high water, based on controls including the frequency of inundation and salinity exposure. This is controlled by the elevation of the substrate surface relative to mean sea level. Hence mangrove substrates can keep up with sea level rise through vertical accretion. Some of this accumulation will be from organic matter production, but this can be augmented by external inputs of sediment from rivers. Rates of accretion reveal that mangrove ecosystems are highly vulnerable to projected rates of sea level rise. Mangroves of low relief islands in carbonate settings that lack rivers are probably the most sensitive to sea level rise, owing to their sediment-poor environments and hence poor rates of vertical accretion. Mangrove response to sea level rise has been investigated by reconstructing Holocene analogues in the Cayman Islands, Tonga and Bermuda. Radiocarbon dating of stratigraphy determined a peat accretion rate of 1 mm/year for all locations. Recession of mangrove forests and replacement by lagoon environments are shown to occur during more rapid sea level rise. On Grand Cayman, 20 km^2 of mangroves receded between 4080 and 3230 years BP. In Tonga, a large mangrove swamp that had persisted from 7000 to 5500 years BP, retreated when rates of sea level rise exceeded 1.2 mm/year.

In Bermuda, present rates of sea level rise exceed 1.2 mm/year, and contemporary recession of the seaward margin of mangroves has been demonstrated. The extensive coastal mangrove swamps of southern New Guinea (Irian Jaya) are also retreating from rising sea level. This demonstrates that, while low island mangroves are likely to be the most sensitive to sea level rise, continental margin mangroves will also suffer disruption and retreat. Mangroves have the capacity for extensive establishment under conditions of stable sea level, but are highly prone to retreat under conditions of sea level change.

Linking temperate and arctic zones: managing the coast for migrant birds

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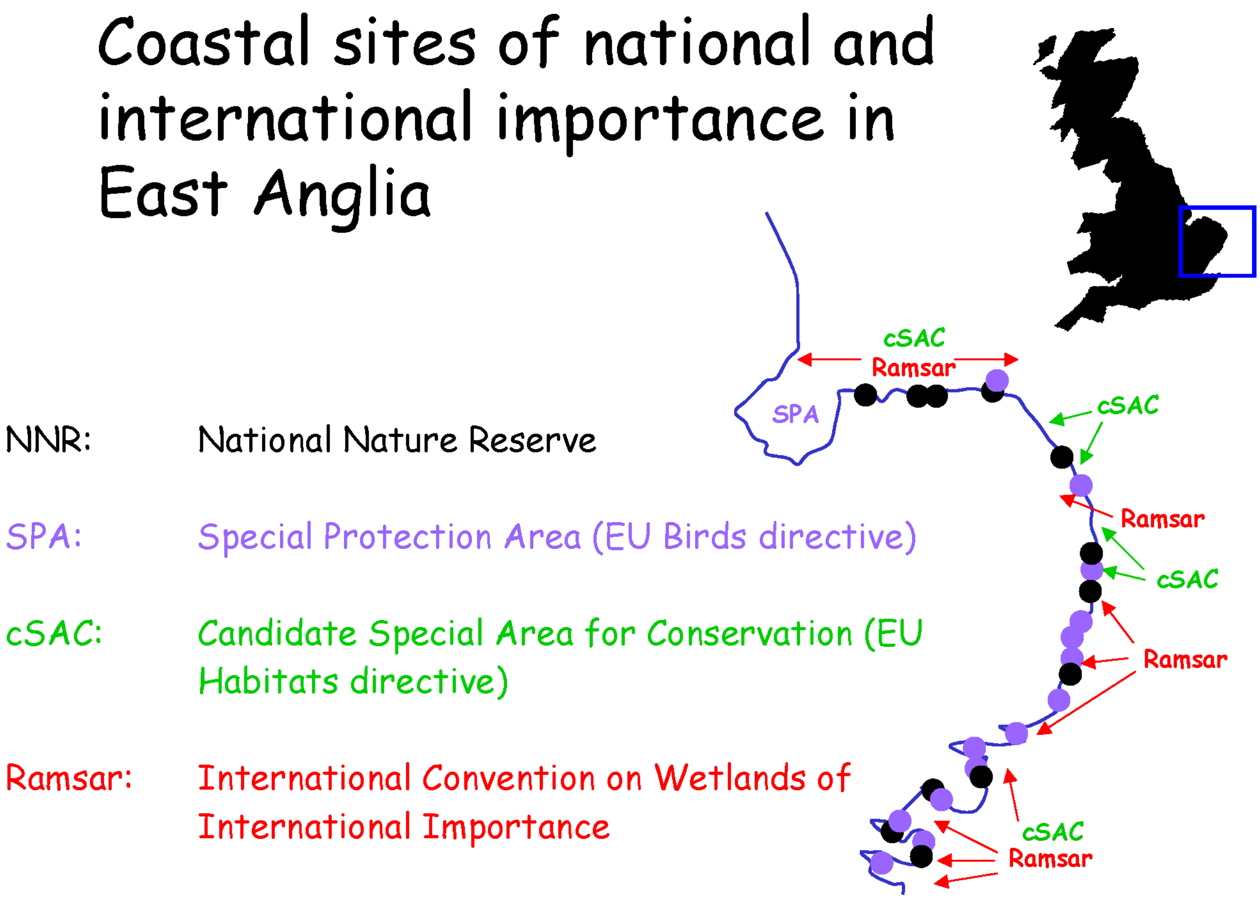
Arctic zones and low-lying coastal areas are amongst the regions that are most vulnerable to the impacts of climate change and associated sea level rise. Migrant bird species that move between arctic and coastal temperate regions on an annual basis may thus face dramatic changes to the habitats that they use at both ends of the migratory range. This is particularly true for the many high arctic breeding species that are almost entirely restricted to intertidal habitats in temperate zones during winter. Coastal management in temperate zones for migratory birds must therefore take account of both breeding and winter season processes, and any interactions between the two.

Changes in climate and sea level can potentially influence bird populations through a suite of direct and indirect routes in both the breeding and wintering seasons. For example, northward movement of the tree line in the arctic (Huntley *et al*., this volume) may reduce the area of tundra available for migrant birds at the same time that sea level rise and changing precipitation and temperature patterns may alter the structure or quality of temperate wintering areas. Whereas climate change and sea level rise may be the primary drivers of change in the arctic, in temperate zones policy responses to climate change are likely to have a more direct and immediate bearing on biodiversity. It is thus critical that policy decisions in the coastal zone are informed by species-level studies that address the complexity of the processes influencing population responses to climate change. Biodiversity conservation in temperate coastal zones is structured through a network of site designations, underpinned by national and international legislative frameworks (Figure 1). Decisions relating to the management and long-term sustainability of these sites are key in maintaining networks for migratory species.

Detailed studies of Icelandic black-tailed godwits, *Limosa limosa*, across the migratory range (Figure 2) have shown how site quality influences individual survival and breeding success and how these processes interact across locations thousands of kilometres apart. This information can be used to assess how changes to breeding and wintering habitats in response to climate change will influence population size and distribution. This provides a useful model for identifying the range of mechanisms by which climate change can influence migratory populations and for predicting population-level responses to climate change.

It is not, however, sufficient to consider the ecological responses of species to potential climate change in isolation. Coastal management for migratory species requires multi-disciplinary, integrated approaches in which models of structural changes to coastlines and consequent impacts on habitat structure and distribution are linked to models of species' responses to climate change and sea level rise. The Regional Coastal Simulator, which is being developed at the Tyndall Centre, aims to integrate these processes to provide a tool for coastal managers to explore the consequences of sea level rise and associated policy decisions in East Anglia.



Coral reefs and global climate change: implications of changed temperatures, sea level, atmospheric carbon dioxide and cyclone regimes

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Global climate change poses a substantial risk to the biodiversity, ecosystem functioning and productivity of coral reefs worldwide, and thus threatens their socio-economic value to human societies. In addition to impacts from climatic change, coral reefs are also under pressure from human activities (eg pollution, harvesting and coastal development) and natural stressors (eg crown-of-thorns starfish and disease).

Historically, these ecosystems have typically been managed through marine protected area systems that focus on the threat from readily identifiable and 'tangible' anthropogenic activities such as fishing and development projects. Incorporating the concept of climate change into the management of marine ecosystems is a relatively recent development that has yet to become widespread. However, it is increasingly evident that it is important to view the potential impacts of climate change in context with the other influences acting upon coral reef ecosystems.

In terms of climate change, increasing sea temperatures are a matter of major concern for coral reefs throughout the world. Coral bleaching is a stress response where the algae symbionts (zooxanthellae) are ejected from the coral host, depriving the coral of nutrition from the products of photosynthesis. Death of the host may result in severe cases. Bleaching can be triggered by a variety of stressors, but temperature-related events are the most widespread. Coral reefs have already suffered major mortalities in many parts of the world as a result of high-temperature events, and there are projected increases in the number and magnitude of anomalously warm episodes. Increasing global sea temperatures may allow further expansion of coral reefs into the sub-tropics, but such processes are likely to be too slow to compensate for the loss of coral reefs to increased bleaching impacts associated with rising temperatures. Also expected to increase are the intensity and breadth of the destructive impact of extreme cyclones and flood plumes.

On a positive note, cyclones can be beneficial to coral reefs by encouraging mixing of surface and deep water, thereby cooling temperatures for a few days, which could be critical during times of harmfully warm waters. Rising sea level may promote growth of some shallow reef communities currently limited by water depth, but some deep areas may suffer from reduced light intensity as water depth increases, particularly where vertical accretion rates are reduced in stressed reefs. Increased atmospheric CO_2 will marginally reduce the alkalinity of reef waters, causing an increase in the rate of chemical dissolution of existing reef limestone, and a decrease in the deposition rate and strength of new limestone deposits. The net effect of climate change on coral reefs will depend on their ability to adapt, but these ecosystems are generally regarded as already living near or at their thermal tolerance limits.

Reef systems are highly heterogeneous in relation to the various influences acting upon them, which include responses and vulnerabilities to temperature-related bleaching events. When considering potential impacts of global warming, a marine park manager will want to know which areas of reef are more likely to escape heat stress or are more resistant to the impacts of climate-related bleaching. Coral bleaching research at AIMS includes spatial risk assessment and forecasting of ecological responses under various IPCC (Intergovernmental Panel on Climate Change) scenarios. Modelling spatial variation in the likelihood of reef areas being exposed to harmfully high temperatures combines regional sea temperature predictions, local patchiness from satellite-derived sea surface temperatures and data on bleaching thresholds. The Great Barrier Reef suffered a major bleaching event in 2002, and systematic ecological assessments of this event provided data on taxonomic patterns of coral survival, injury and death. Mapping the future risk in terms of ecological impact and recovery will be relevant to short-term interests of the tourism industry, and also to management actions seeking to sustain the long-term ecological structure and functioning of coral reefs. The products of this research will be important tools for decision-makers who can implement the scientific findings into policy-making processes.

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Figure 1. *Sea temperature anomalies on the Great Barrier Reef in 1997–98 and 2001–02. The highest sea temperature on record occurred in 2002.*

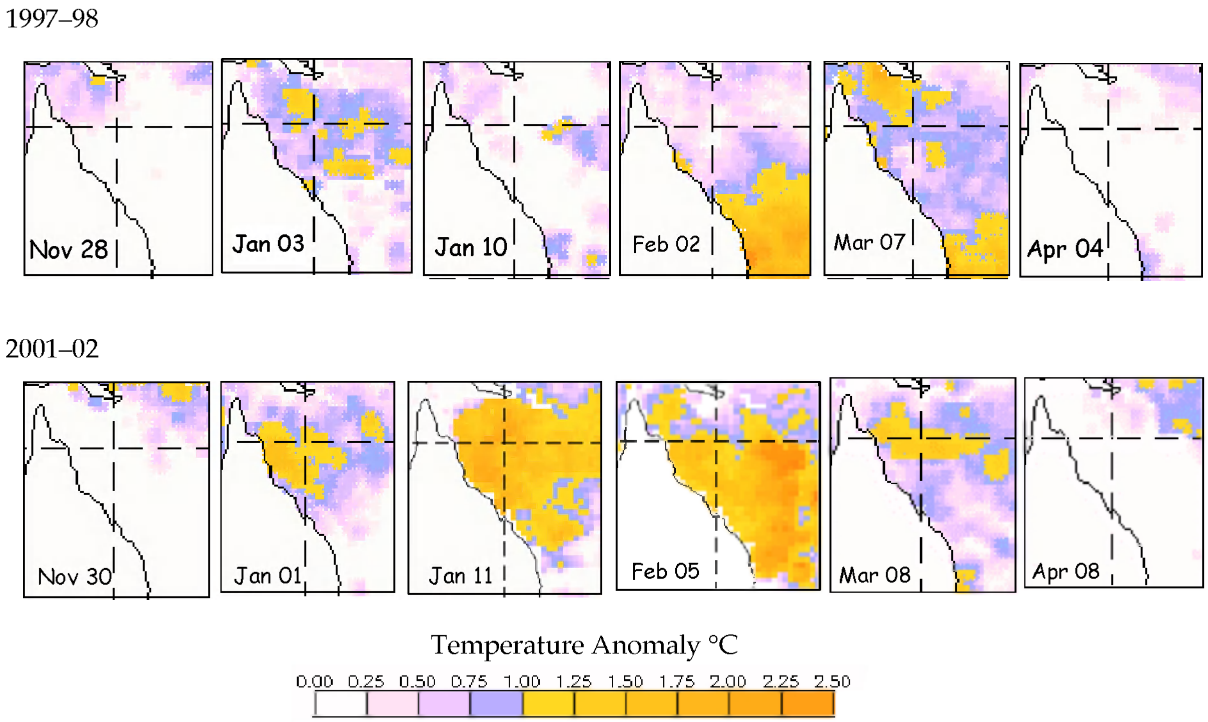
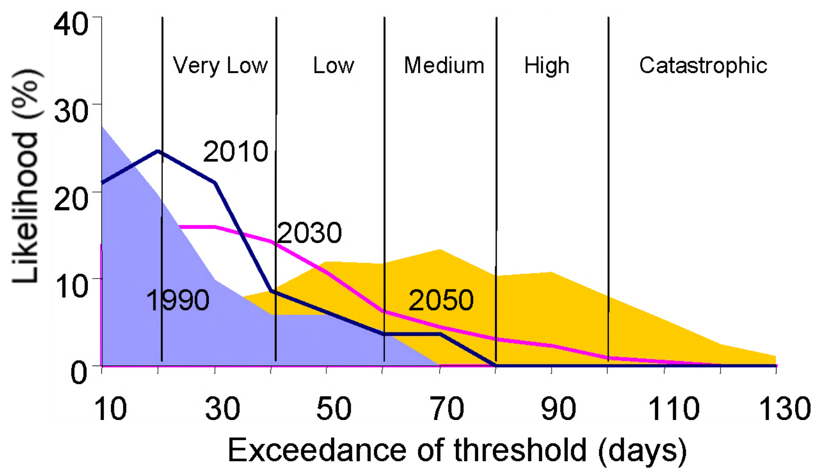


Figure 2. *Recent and projected probability distributions for durations of periods of exceedance of threshold sea temperature for damage to corals on the Great Barrier Reef. Vertical lines separate classes of expected coral damage.*



Key points raised in session discussions

Global change session – chaired by Martin Parry, Hadley Centre, UK Meteorological Office

- At the global level, drought stress and sensitivity to drought will increase in the south
- It would take between 500 and 1,000 years to release five metres of the Arctic ice sheet as water in the worst-case scenario
- Europe will remain a carbon sink, but less so than at present; tundra regions may become a source of carbon
- Species will need to move at a rate and order of magnitude greater than they did at the end of the last glaciation to maintain their geographical range in the same climate envelope
- There are significant uncertainties about the relationships of species distribution and climate change, and about species' abilities to migrate and re-distribute; validating climate envelope models will be essential to successful conservation planning
- Under some assumptions, models indicate that 10% of high latitude species may become extinct due to climate change pressures and associated doubling of atmospheric CO_2; species with narrow habitat breadth in other areas may approach high latitude losses
- Anthropogenic pressures – socio-economic, and land use changes – are likely to be vastly more important as drivers of biodiversity change than climate change. These pressures, too, will of course be modified by climate change
- Habitat fragmentation is a key factor affecting the ability of species to respond to climate change by changing its current distribution
- Public relations drives the democratic process in the western world and is an important tool in determining what society cares about and, therefore, cares for; tourism indicator species could be developed and used to prioritise biodiversity conservation.

Forests session – chaired by Jeff Sayer, WWF International

- Should conservation objectives be aimed at static or dynamic species goals?
- There is a strong trend for climate to be considered a predictor of species distribution, but other factors are also involved and may be used as future predictors
- There is a different response by species to fire in south east Asia from that in Africa; fires are not universal across the globe and species' responses are varied; fires can be managed by manipulating fuel loads
- Increasing the size of protected areas increases linkage between different areas, allowing species to adapt to disturbances and changing conditions, and allowing increased conservation management input in the areas outside the protected areas.

Marine session – chaired by Simon Jennings, Centre for Environment, Fisheries and Aquaculture, UK

- Most fisheries' models do not take account of environmental variability
- Fishing mortality is too high for most stocks
- New marine reserves in New Zealand are a great success and have resulted in significant increases in the numbers of mature fish
- Most marine nature reserves (MNRs) are close to land; none of the few in the UK are outside coastal waters; nature reserve corridors are needed in the seas; climate change is not a factor in MNRs yet
- Marine systems are dispersal-dominated and a 10,000-mile scope is not unusual; this needs to be reflected in fisheries' management and marine conservation
- Science is important in assisting policy-making

- The single species policy focus has not worked for fisheries. Ecosystem management is gaining prominence as a useful management and policy idea, although it is conceptual and the practicalities are as yet unknown
- A framework for learning and change is needed, as well as the development of management to allow change
- There is a tension between scientific rigour and urgent need for action
- Climate change impact on marine food webs and energy and nutrient flows is greater than on biodiversity
- Marine knowledge lags vastly behind terrestrial biodiversity knowledge and, in comparison with terrestrial habitats, marine ones are very poorly looked after
- The slow growth and maturation of much maritime biodiversity exacerbates problems in the marine ecosystem
- Fishing is the major impact on marine ecosystems at present, not climate change
- Land-based nutrient input can be important in driving marine ecosystems; at the Great Barrier Reef, fishermen are using eutrophication as decoy for overfishing
- Biodiversity conservation involves ecosystem structure and function at all levels – this is a powerful definition for conservation in the political context.

High latitudes and montane session – chaired by David Gibbons, RSPB, UK

- The panel was asked if climate change is the greatest threat to biodiversity in high latitudes and altitudes:
    - In the Antarctic, scientists may be a significant threat, despite the strict controls in place
    - For the Arctic, climate change is an important threat, but human development pressures are probably greater
    - In the tropical montane forests of north east Australia, climate change is a massive threat to biodiversity; invasive weeds and feral animals also pose threats
- Climate change in the Arctic is likely to rapidly reduce the available geographical area for high tundra species, creating enclaves and habitat fragmentation
- The impacts of tundra loss on Arctic breeding birds should be assessed in combination with winter habitat losses
- Land managers and tourists could be brought together to form a political lobbying force for conservation, although some land managers are hard to convince of the long-term impacts of climate change
- Ozone depletion in the Antarctic causes ultraviolet damage to phytoplankton, which may be contributing to cooling, although:
    - this may be ameliorated by high snow cover at times of greatest UV exposure
    - phytoplankton may develop adaptive pigmentation, although the energetic cost of this response is unknown.

Managed landscapes session – chaired by Brett Orlando, International Union for Conservation of Nature, Switzerland

- The panel was asked what the broad implications of climate change are for conservation policy:
    - There should be a concentration on montane and other heterogenous habitats
    - Most species have different requirements, and therefore require different management responses
    - More political pressure for conservation needs in a changing climate should be applied and brought to focus

- Research into the impacts of a wider range of climate change scenarios is required, as well as an assessment of the effect of reducing the increase in global mean temperature (from, say, 4°C to 2°C) upon biodiversity
    - There needs to be a recognition that climate change is only one of a range of factors affecting the distribution of species
    - Land use change will have a major impact on species' distributions in managed landscape
    - Economic as well as ecological messages should be used to build support for biodiversity conservation
- Adaptive site management needs to be better understood, by establishing research programmes and feedback loops linking scientific knowledge with site management and conservation policy processes
- There are political, legal and social difficulties in accepting a new dynamic in nature conservation; policy mechanisms tend to offer more flexibility than legal ones but are prone to misuse
- Establishing goals/objectives for management will be difficult; broad extremes represent either accepting change or holding out invaders
- As well as biological factors, there are cultural, social, economic and legal issues
- Managing sites for resilience may make it harder for wildlife to move into protected areas
- There is very little field-based experimental work or evidence-based information on the adaptation of biodiversity to climate change; this is a key area in which research should be developed
- Introduced invasive species should be tackled at once, without delay
- Communication to the public is essential, to increase understanding of climate change-biodiversity issues and hence support for biodiversity conservation as climate changes; many naturalists will see climate change as a good thing with new species to see; it is hard for Britons to view global warming as a bad thing.

Coastal session – chaired by Andrew Watkinson, University of East Anglia, UK

- The panel was asked whether scientific work is undertaken in a way that is designed to help conservation:
    - Scientists and research programmes are providing better information for conservation, but are not are not yet focused enough on conservation delivery. There is a need to improve dialogue with conservation and other stakeholders
    - There are good links in the coral reef world, which could be improved by developing better links with the tourist and fishing interests
    - Site managers want answers faster than rigorous scientific research can usually provide them; a risk assessment approach could be developed to help overcome this
- Conservation needs good science to manage coastal zones effectively
- Scientists may often understand processes essential to good biodiversity management before conservationists. There is a need to establish better dialogue between the two communities and, in some cases, make better use of existing data
- Conservation organisations should establish closer links with the research funding bodies, to help inform the direction of the research councils' work and improve the defining of research areas and objectives. Scientific direction should be more directly relevant to societal issues and less driven by the need to publish scientific papers, though peer review of research results remains essential
- There is increasing recognition of the wider value of biodiversity and its conservation, which should be reflected in research funding
- Establishing a good dialogue within a multi-stakeholder research project is hard work and takes considerable time and expense, but ultimately can contribute enormously to the smooth running and focus of the research

- For coastal process research, flood defence is usually the primary driver. Establishing dialogues and building shared objectives between conservation interests and engineers is both hard work and enormously rewarding in terms of practical site benefits.

Synthesis and outlook: a discussion led by Camille Parmesan, University of Texas, USA

The global climate has been very stable for the last 10,000 years, at a warmer level than for three million years. The Medieval Warm Period and Little Ice Age were regional, not global events. Most of the Earth's current species, therefore, have not experienced major climate change.

Only the positive results of scientific research tend to get published; neutral results or those contrary to expectations are less likely to become known. This contributes difficulty to estimating the response of species to climate change. However, 460 species of 920 species studied have shown distributional change and, for 81% of these, climate change is the cause of change. Over the last century, 50% of species are estimated to have responded in some way to climate change.

There are problems with uncertainty in predicting future biodiversity responses to climate change. These stem from several sources, including downscaling global climate models to regional and local scales, the limitations of available computing power and the uncertainties of both the climate and biogeographic models. Science is not yet able to predict species' vulnerability. We have poor data on species distribution and abundance for most of the world, and land use change is difficult to quantify.

Nonetheless, there is consensus on the threat that climate change will bring to global biodiversity. Species with severely bounded distributions are under high risk from climate change, as are species with poor dispersal capability and restricted ranges. A figure of 10% species extinction over the next 100 years has already been mentioned at this conference – along with a health warning about the robustness of the estimate. The level of species loss will be directly related to the extent to which mankind can limit global warming. If we manage to contain global warming to 2°C, there will be some species loss but there are conceivable management options for the conservation of global biodiversity. At 4°C global average temperature rise, there will be many species lost, few management options and enormous financial cost. At the uppermost predictions of around 6°C temperature rise, the outlook is dire.

It is, therefore, imperative that global warming is contained to 2°C by the end of this century. If we don't achieve this, the future is bleak for both biodiversity and people. Scientists and conservationists must get more political, to get our messages across to world leaders and ensure that the necessary action is taken to limit global warming.

Climate change should also influence our research. The Red Lists need reassessing, to incorporate the impacts of climate change on existing species and to identify new species vulnerable to climate change. We need to collate existing data worldwide. We need to develop the modelling of species' responses to climate change and to compare modelled outputs with the results of empirical research. The many strands of research need to be brought together, to provide the best information possible to guide the development of biodiversity conservation against the threats of climate change.

Synthesis and outlook: a discussion led by Bill Sutherland, University of East Anglia, UK

There are nine key policy issues, which must be addressed, that are fundamental to biodiversity conservation:

- Reduce CO_2 emissions. We must constrain global warming to 2°C
- Adopt the triage approach of prioritising species and habitats conservation. Use the broad categories of: no hope; intervention might save; and non-threatened
- Nature reserve selection. Increase their evolutionary capacity in as many ways as possible. Current ideas include developing more resilient reserves, establishing biodiversity corridors, preparing new habitats in new areas of predicted future species' range and increasing the size and diversity of nature reserves
- Practical species and habitat management. Use existing and new techniques, developing, for example, from fire, access, grazing and water. Consider adding climate-adapted genes from other locations
- Explore habitat restoration opportunities. Find ways to get the £2.3 billion EU agricultural subsidy budget to deliver more for biodiversity. Link health benefit opportunities to habitat restoration; seek to build biodiversity benefits into the vast amount of funding that is available for a variety of purposes. Link with existing activities, eg exploit the natural water storage of coastal saltmarsh in coastal defence works
- Legislation. Needs to be more flexible to address species introductions, aliens and the current focus on the maintenance of the *status quo*
- Making decisions in the face of uncertainty. Develop decision-making to cope with poor scientific knowledge and uncertainty. Adopt new techniques, eg simulations and alternate states
- Best allocation of resources. Conservationists are prone to over-exaggeration; ensure optimum targeting
- Public awareness. Provide evidence of climate change impacts and models of possible outcomes. Seek to overcome public apathy to climate change and the problems of biodiversity.

Synthesis and outlook: further discussion

- Environmental groups must work globally to ensure that limiting global warming to 2°C is achieved
- The scientific community should work to guide actions on global warming; scientists should outline the timescales, processes and knowledge to inform policy; systems should be developed to learn and improve the understanding of climate change impacts, mitigation and adaptation
- There is patchy awareness of biodiversity and the impacts of climate change: good in Europe, not so good in the USA, for example. The UK has the best data, which should be used to send worldwide messages about climate change effects on biodiversity. Opportunity for BBC documentary; public awareness needs to be developed – too many UK people think that global warming isn't a problem and could even be a good thing
- There is a need to find strong signals for climate change, which can be used to monitor climate change unambiguously, clearly isolated from other factors
- A guide to the likely climate in the 22nd century would be valuable to help define objectives for biodiversity conservation in the 21st century. Different conservation responses are needed for an increasingly warmer world than for one in which warming slows or is stabilised, and for a potential fall in global temperature after a peak
- There is the danger of 'conservation blight' (cf planning blight) whereby people could feel that if species are ultimately doomed, there is little point in providing action and resources for their conservation

- Human population forecasts are important in understanding the future human impacts on biodiversity. Traditional resource management techniques and information are important contributors to assessing biodiversity impacts, which will be further refined by developing adaptive and experimental management, impacts experiments, future technology and societal requirements from biodiversity in a changing planet
- Experimental work is increasingly turning up responses that had not been considered, including a greater number of non-linear responses. Scientists and policy-makers need to look and think outside current experience and paradigms
- Moving the philosophical underpinning of biodiversity conservation away from product-based conservation to more process-orientated approaches may help to allow species, sites and the countryside to respond to changing climate. This must nonetheless be an approach that allows biodiversity to thrive rather than to take its chances in a changing world, but one that may provide better opportunities for recreating habitats in new locations, linking fragmented habitats and facilitating species' movements
- The UK conservation approach is very interventionist, as result of the UK's land-use history; letting natural processes take over a small number of sites should be considered to increase our understanding of biodiversity response to climate change. However, it should be recognized that past human interventions will prevent changes in such areas being entirely natural
- The scale of the challenge is that of keeping global temperature rise to within 2°C; it will include the impact of new technologies on biodiversity, including different ways of generating power and the role of adopting energy efficiencies. Taking forward action on what can be achieved easily, first, is important now; there will be different options and priorities to suit different countries and experiences
- Is carbon sequestration fundamental to stabilising climate change? This question needs to be properly assessed, including both human and biodiversity risks and impacts, to determine the best way forward and to prioritise actions
- Most conservation biologists are not aware of the impacts of climate change – it is a very small part of university courses, although this is now growing in a few cases
- In the USA, awareness about climate change is growing slowly now that President Bush has had to accept the compelling evidence of changing climate. The US Senate passed the need for action in April 2003 but adopting solid policy options and action will be much harder. At the US state and city levels there is considerable action and creative activity to address climate change. Major US contribution is essential to tackle the global problem
- The biggest opportunities for the environmental community are likely to be in connecting conservation concepts and values with other arenas (including agriculture, economics, trade, market realities, science etc), working towards the goal of increasingly finding holistic solutions to mankind's activities, issues and problems.