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Biodiversity and Climate Change: Possible Impacts, Adaptive Response and Research

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INTRODUCTION

Human activities are affecting the global climate and the concentration of various gases in the atmosphere. Global mean temperatures have risen approximately 0.7°C since the mid 1800s and changes in rainfall patterns, sea levels, and rates of glacial retreat have also been detected which are consistent with expectations of 'greenhouse' climate change. The 1990s were the warmest decade ever recorded instrumentally, and the last 100 years were the warmest of the millennium. Last year [2002] was the second warmest on record with 1998 being the warmest. The most recent report of the Intergovernmental Panel on Climate Change [2001] concluded that there is now strong evidence for a human influence in these global climate trends and that these trends will continue for the foreseeable future due to continued emissions of fossil fuels and other greenhouse gases. The most up to date predictions are for an increase in global average temperatures of 1.5–6°C by the end of the present century with regionally-variable changes in rainfall and other climatic factors such as cyclones.

In this paper we discuss the likely impacts of climate change on biodiversity with a particular emphasis on how we can adapt our nature conservation strategies to reduce losses of biodiversity. Our discussion is primarily focussed on terrestrial and freshwater impacts of climate change although many of the concepts and issues are transportable to marine ecosystems. We find that an understanding of the impact of climate change on biodiversity generally adds emphasis to existing nature conservation strategies. However, there are a few conservation strategies we should consider that we would not otherwise consider in the absence of climate change. Some of these new strategies require further management-oriented theoretical and empirical research before we can be sure of the best way to proceed.

SECTION 1: WHAT ARE THE POSSIBLE IMPACTS OF CLIMATE CHANGE ON BIODIVERSITY AND WHAT ARE THE MECHANISMS THAT DRIVE THOSE IMPACTS?

The biophysical changes associated with climate change likely to have a significant impact on biodiversity include both direct and indirect effects.

Direct effects

Changes in temperature, water availability and CO_2 concentration will directly affect the physiology of most species. In animals, temperature can affect metabolic rate, fecundity, survivorship, sex ratio, length of oestrus, hormone release and parasitic infection rates. Warmer conditions may advance flowering and fruiting in some plants, hasten development time in many animals and increase decomposition rates [thus affecting nutrient cycling]. Increased CO_2 concentration enhances photosynthesis in cool-season [C_3] plants, water use efficiency and growth in many plant species, and alters the chemical composition of plant tissues. The altered chemical composition of plants affects herbivores. Increased CO_2 concentrations will affect nitrogen fixation, decomposition, and respiration rate in micro-organisms and fungi.

Indirect effects

Species will be affected indirectly by climate change through altered interactions with other species. For example, temporal decoupling of life-cycle events between some species, such as plants and pollinators may occur via changes in flowering phenology and/or pollinator emergence times. Many species will also be affected by changed competitive relationships. C_3 plants may be advantaged over warm-season (C_4) plants under increased CO_2, because their growth will be relatively more enhanced. Early-successional species with fast growth rates and good dispersal may also be strongly advantaged, and landscapes may become increasingly dominated by a few opportunistic, 'weedy' species. Species with high reproductive rates and short generation times will be advantaged, including many parasites and pathogens.

Population dynamic effects

Ecology is the study of the distribution and abundance of organisms. Conservation biology is particularly concerned with species whose distribution and/or abundance is unacceptably low. The abundance and distribution of populations are driven by birth, death and movement. While much work in the climate change arena has concentrated on the direct and indirect effects above, little work has integrated those effects into the population dynamic framework necessary to explore conservation biology problems. Figure 1 shows a new framework for connecting direct and indirect effects to population dynamic effects. This is an important new area of research that will be essential for us to make conservation decisions where climate change effects are believed to be important.

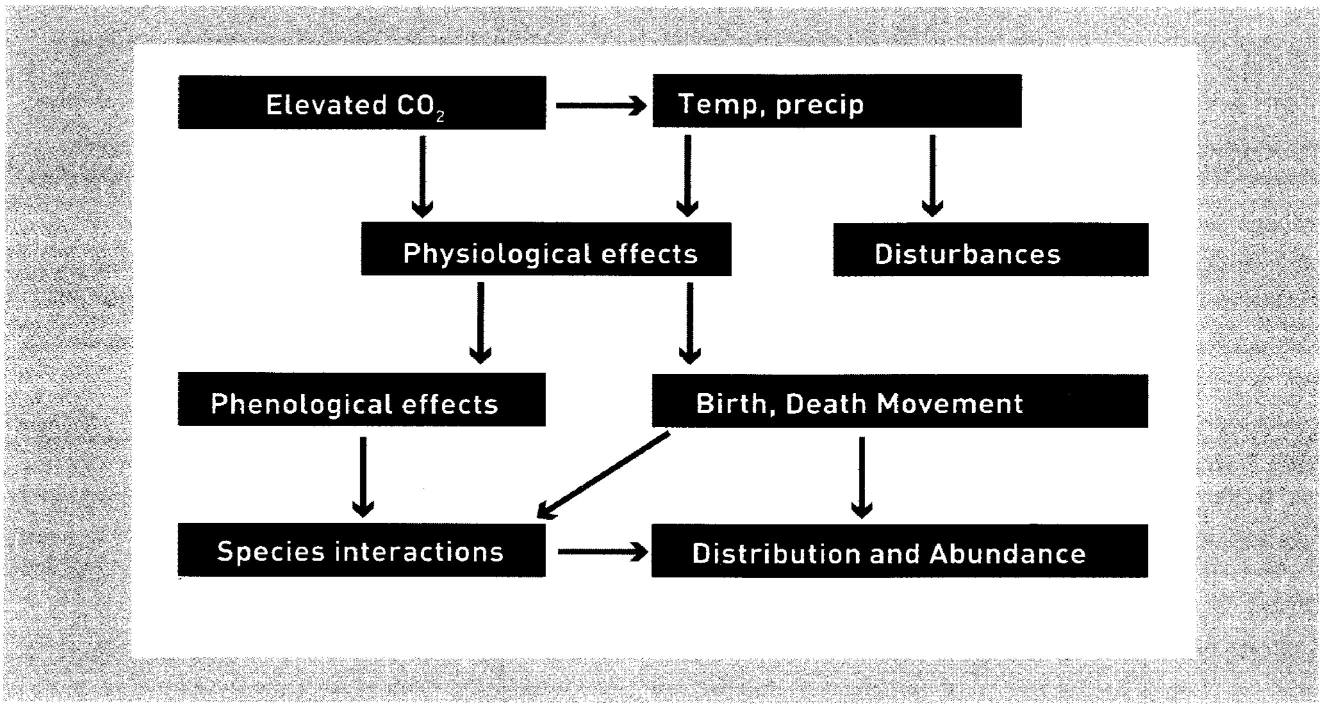

Figure 1: The influence of direct and indirect effects of climate change on the population dynamic processes of birth, death and movement. These in turn drive distribution and abundance, along with feedbacks with species interactions, to determine how much different species will be affected. (Note that feedbacks from the biota to climate change have been ignored in this diagram).

SPECIES RESPONSES

Species may respond to changes in climate in a number of ways.

Tolerance

For species that use the environment at a fine spatial scale (e.g. insects and small plants), tolerating future climate change may involve changing behaviour to exploit a suitable microclimate. Some species may also have enough phenotypic plasticity and/or genetic variability to readily withstand the predicted changes. Species that currently have a broad geographic range and therefore broad climatic tolerance may undergo some contractions or expansions at the edges of their range, but remain largely unaffected, at least over the next few decades. However, some species with broad geographic ranges will consist of several ecotypes, each adapted to local climate. These species may be just as vulnerable to rapid climatic changes as species with restricted ranges.

Genetic adaptation in situ

Species with short generation times and rapid population growth rates may undergo microevolutionary change (in behaviour, physiology or morphology) in response to the changing environmental conditions *in situ*. However, the speed with which environmental change is predicted to occur means that adequate response through adaptive evolution is unlikely for many species. Micro-organisms, some invertebrates, and early successional plant species may be the exceptions, by virtue of their broader range of tolerance as well as their short generation time and hence potential to evolve faster. These species may spread at the expense of others that are slower to evolve.

Shifts in distribution

The ability of species to track changing environments will depend on the rate of climatic change, the migratory potential of the species, changes in local disturbance regimes, and physical obstacles in the path of migrating individuals. During warming events in the past, species colonised new habitats toward the poles, often while their ranges contracted away from the equator as conditions there became unsuitable. Equatorial organisms expanded into the temperate zone and temperate ones into the boreal zone. Fossil pollen records of Northern Hemisphere deciduous trees, for example, indicate that some species migrated in response to climatic changes at average rates of 1–20 km/decade. Simple extrapolations of these rates have been used to predict future migration rates. The general consensus has been that because future warming rates may be 10–60 times greater than any since the last glaciation, most species will be unable to migrate fast enough to keep up with shifting climate zones. Recent modelling, however, suggests that the speed at which a species can migrate is more dependent on the probability of relatively rare long distance dispersal events than on average dispersal distance, casting doubt on the usefulness of previous extrapolations. The rapid rate of some contemporary invasions (5–13 km/yr) suggests that long distance dispersal in some species certainly does occur. Apart from capacity to disperse, the main factor that will limit the ability of species to keep up with the moving climate will be the availability of suitable establishment sites. Human land use patterns and the increasing fragmentation of natural landscapes now present formidable barriers to natural migration (given the above arguments, fragmentation/land-use change is likely to also be important to rare, long-distance dispersal events, as it reduces the likelihood of the propagule 'landing' in a favourable site). Community disruption and inter-specific competition, particularly with weedy species and aliens, will play a major part in migration success. The availability of suitable substrate is also a requirement for movement and in many cases, suitable mycorrhyzal fungi and bacteria will need to be present in newly-colonised soils.

Extinction

Many species will be unable to tolerate the changing environmental conditions within their current range, and will also be limited in their ability to move to more suitable habitat. These species face extinction, either as a direct result of physiological stress, or via interactions with other species. The most vulnerable species will be those with long generation times, low mobility, highly specific host relationships, small or isolated ranges, and low genetic variation. Species such as vertebrates with large home range requirements, and those dependent on precise climatic triggers that determine aspects of their life cycle will also be at risk. Populations within reserves, which are typically remnants of larger original populations reduced through habitat loss or over-harvesting, may be particularly vulnerable.

Changes in physiology, phenology and distribution of individual species will alter competitive and other interactions between species, with consequent feedbacks to local abundance, geographic ranges and the composition of communities. The precise nature of these changes is difficult to predict, because each species within a community or ecosystem will respond individually. Despite some uncertainties however, some communities such as coral reefs, alpine habitats and wetlands are considered particularly at risk.

SECTION 2: IS THERE ANY EVIDENCE FOR THE IMPACT OF CLIMATE CHANGE?

Analyses of long-term datasets in the Northern Hemisphere indicate many species from different taxonomic groups, trophic levels and habitats have already responded to the anomalous atmosphere and climate of the 20th century in ways consistent with predictions of likely responses to climate changes. Recent reviews have documented shifts in species distributions toward the poles or upward in elevation, and progressively earlier life cycle events such as flowering, reproduction and migration (Hughes 2000; McCarty 2001; Walther et al. 2002; Parmesan & Yohe 2003; Root et al. 2003). While it is almost impossible to dissociate climate change impacts from other human-induced impacts in many of these studies, the weight of evidence that climate change is already affecting biodiversity is strong. Indeed, failing to reject the null hypothesis of no impact of climate change on biodiversity now seems scientifically untenable.

The polar regions, as expected, have recorded the most dramatic changes so far. For example, in the subantarctic zone mid-winter temperatures have increased by about 4°C at Faraday Station on the Antarctic Peninsula since the 1940s. Over the same period, localised reductions in ice cover of up to 35 percent have been reported, as well as melting of permafrost to a depth of 1m. There is evidence that warming is affecting the distributions of taxa as diverse as bryophytes, vascular plants, penguins and marine mammals in both the Arctic and Antarctic (e.g. Smith 1994; Krajik 2001).

In alpine areas, upward colonisation and establishment of plants has been widely reported with increases in species richness at high elevations in the Swiss Alps and upward extensions of the treeline in many mountain areas (Grabherr et al. 1994; Peterson 1994; Pauli et al. 1996). In some mountainous areas of the tropics, such as the cloud forests of Costa Rica, rising sea temperatures have resulted in the air becoming warmer and drier. Twenty species of amphibians have apparently disappeared since 1987 and both bird and lizard populations have also been affected (Pounds et al. 1999).

Off the Californian coast, sea surface temperatures have increased 0.8°C over the past 40 years. In the same area, substantial declines in abundance of various groups have been reported, including zooplankton (70 percent), sooty shearwaters (90 percent), macroalgae (70 percent) and reef fish (15–25 percent) (Roemmich & McGowan 1995; Holbrook et al. 1997; Veit et al. 1997). In the same area, a shift in species composition from dominance by northern to southern species of both reef fishes and intertidal invertebrates has also been documented, consistent with the prediction that polewards migration of species will occur in response to moving climate zones (Barry et al. 1995; Holbrook et al. 1997; Sagarin et al. 1999). Increasing incidence of thermophilic marine species has been recorded in the Adriatic and North Seas at the same time as declines in the incidence of cold-affinity species (Nehring 1998; Dulcic & Grbec 2000; Sturm et al. 2001).

Range shifts have also occurred in some terrestrial species. Substantial numbers of bird and butterfly species in both Europe and North America have shifted their range northwards by up to hundreds of kilometres over the past century (Parmesan et al. 1999; Thomas & Lennon 1999). These shifts in range are generally precipitated by changes in birth and death rates at the level of the population. A detailed survey of local populations of Edith's checkerspot butterfly *Euphydryas editha*, for example, showed that populations in the northern parts of the range, and at higher elevations, were more likely to have persisted over time than southern and lower populations (Parmesan 1996).

There is also evidence that changes in the timing of important life cycle events are already occurring in some species (Peñuelas & Filella 2001; Root et al. 2003). The active growing season for plants in the northern latitudes has lengthened by about 11 days since the 1960s; in effect, spring now starts 6 days earlier, and autumn nearly 5 days later (Menzel 2000). Increased photosynthetic activity by plants, as indicated by greater, and earlier, drawdown of CO_2 has been recorded (Keeling et al. 1996; Myneni et al. 1997). Increasing spring and summer temperatures in Britain and Europe are the most likely explanation for recently detected trends toward earlier egg-laying and more rapid development times in many bird species (Crick et al. 1997; Crick & Sparks 1999). Earlier flying dates for adult insects have been recorded in butterflies and aphids (Fleming & Tatchell 1995; Roy & Sparks 2000), while in several species of British amphibians, spawning dates have also advanced, with every 1°C increase in annual maximum temperature corresponding to an advance of 9–10 days (Beebee 1995). Trees such as the poplar flower 26 days earlier in Canada than they did a century ago (Beaubien & Freeland 2000). Changes in phenology are already resulting in mistimings of species interactions such as predator-prey relationships (Visser & Holleman 2001).

While it is probably too early to detect genetic changes in response to warming for most species there is nonetheless some evidence for genetic changes in a few, e.g. *Drosophila* (Rodríguez-Trelles & Rodríguez 1998), pitcher-plant mosquitoes (Bradshaw & Holzapfel 2001) and red squirrels (Réale et al. 2003).

Most of the trends detected so far are for individual species, but the cascading of these individual responses to increasingly alter the composition of whole communities and ecosystems seems inevitable. If such climatic and ecological changes are already being detected with an average global warming of 0.6°C, many more profound effects on species and ecosystems will occur if temperatures reach levels predicted by some of the IPCC (2001) scenarios, which run as high as 6°C by 2100.

Australia

Climate trends in Australia have been consistent with global patterns, but due to the lack of long-term biological datasets available, measurable impacts of climate change for Australian species and communities are limited. Nonetheless, there is evidence of changes in species distributions and life cycles consistent with having a climate-change component (reviewed in Hughes, in press). These include: increasing establishment of snow gums into sub-alpine meadows (Wearne & Morgan 2001), saltwater intrusion and mangrove establishment into formerly freshwater swamps, especially in the Northern Territory (Mulrennan & Woodroffe 1998), increased wheat yields correlated with a decline in frost frequency and duration (Nicholls 1997), rainforest expansion into eucalypt woodlands (Harrington & Sanderson 1994), increased frequency and intensity of coral bleaching as a result of increasing sea surface temperatures (Lough 2000), and changes in the distribution and/or abundance of animals such as reptile ticks, (Bull & Burzacott 2001), bats (Tidemann 1999), feral mammals (Green & Pickering 2002), migratory birds (Baxter et al. 2001; Green & Pickering 2002) and seabirds (Dunlop 2001; Bunce et al. 2002).

SECTION 3: HOW SHOULD WE ADAPT OUR CONSERVATION POLICIES TO ADAPT TO CLIMATE CHANGE WITH THE OBJECTIVE OF MINIMISING BIODIVERSITY LOSS?

Having established that climate change will affect biodiversity, we now wish to consider our strategic response. Several papers (Hughes & Westoby 1994; Williams et al. 1994; Pouliquen-Young & Newman 2000; Howden et al. 2003) have discussed conservation strategies to ameliorate the impact of climate change on biodiversity. Many of the strategies already exist — climate change only serves to emphasise their importance. In this section we place particular emphasis on the strategies that are most closely linked to adapting to climate change.

Biodiversity conservation — old messages underlined by likely climate change impacts:

- decision-making on a biogeographical basis;
- recognition of the role of off-reserve conservation;
- connectivity across environmental gradients to provide species with opportunities to move with shifting climate zones;
- risk-spreading to deal with catastrophes; and
- increased quarantine plus early detection and eradication to deal with more invasive (e.g. avian malaria), 'sleeper' weeds that 'wake-up' etc.

For the above issues an expectation of climate change merely underlines the need for more effort or consideration. In the past a great deal of conservation practice and theory relied on a tacit assumption that the patterns and processes that affect biodiversity are static e.g. the mix of species within a community, the fundamental niches of species, and the presence of species in suitable habitat. Modern conservation biology recognises that there is no mythical equilibrial state for ecosystems. New species appear, catastrophes and environmental variability push systems around, sometime to places or states from which they cannot recover, and many ecological processes alter dramatically in space and time. Climate change underlines this reality and means we need to take a more dynamic view of conservation strategies, being prepared to alter strategies as the state of a system changes, and learn new things about ecosystems as we manage them. Conservation in this sense is far from preservation, rather, it is an attempt to keep as many options open as possible in a fast changing world. At present Australian science, policy and institutions are not geared to provide advice on managing a dynamic world, but instead seek non-adaptive strategies that attempt to deliver certainty, but also lock us in to particular land tenure and management approaches, like conservation parks and intensive agriculture. Adaptation to climate change is all about keeping as many options open as possible. Permanent allocation of land or sea to specific uses reduces flexibility and hence our capacity to respond.

Knowledge of climate change means we should consider the following new conservation strategies:

- selection of conservation areas based on non-stationary environmental features. While our arguments above emphasise the need for more flexible land tenure and management, there are no institutional arrangements in place that would facilitate such flexibility. There is no theory or practice of spatially dynamic conservation planning. Western notions of land tenure are not consistent with optimal landscape management.
- conservation of climate change refugia. Certain parts of the continent may be either buffered against climate change, and/or contain sufficient habitat heterogeneity to accommodate many species whose requirements will change with climate change. While we suspect that areas of high topographic variability may be refugia, we have few other clues as to where such places may be. If we could identify these places they should be high priorities for preservation and/or landscape-scale habitat reconstruction.

- triage of the climate vulnerable. From the perspective of cost efficiency, those elements of biodiversity that are extremely vulnerable may be best triaged. We know that Australia already faces the loss of a substantial fraction of its biodiversity, with or without climate change. If climate change sensitive species appear to require expensive interventionist strategies to ensure their survival (e.g. captive breeding) then those resources may be more efficiently applied elsewhere.

- deliberate translocations. If we know that the distribution of certain species needs to move more rapidly than the species can move unaided, and extinction is likely, we could proactively translocate those species, indeed entire communities, to their likely future distribution. This strategy is risky because of lack of knowledge about which species fit the criteria, and which translocated species may cause problems in their translocated distribution. Considerable research, both theoretical and empirical, is required before this option should be used.

- monitoring of sensitive species and ecological processes. Australia has a poor track record of long-term ecological monitoring, hampering our capacity to detect the magnitude and consequences of climate change. A lack of long-term monitoring sites affects our capacity to choose between different management options. Carefully targeted monitoring of biodiversity and ecological processes may enable us to choose between the conservation strategies outlined above. This would require considerable thought in to what we monitor, and the capacity (power) of that monitoring to deliver improved decision making.

How important are these issues compared to other conservation issues? The PMSEIC report on biodiversity (Morton et al. 2001) emphasised the fact that prevention is better than cure as far as biodiversity is concerned. As far as climate change is concerned, prevention is also clearly the best option given the uncertainty as to whether we could adequately adapt to climate change from a biodiversity perspective.

Given that a certain level of climate change is already unavoidable, how important are the climate change specific conservation strategies compared to other conservation strategies? In general we believe that species measures to adapt to climate change are not urgent in the context of more significant biodiversity crises. Nevertheless an understanding of climate change influences the three major preventative measures identified in the PMSEIC report:

- effective vegetation clearance controls;
- extra quarantine and enhancing early detection and eradication to minimise incursions of pests and disease; and
- water allocation and trading systems that enable effective environmental flow regimes.

Effective clearance controls enhance connectivity in the landscape and increase the likelihood that climate change refugia are protected. Quarantine and early detection and eradication is the most cost efficient mechanism of stopping weeds and pests before they become an expensive problem. A knowledge of climate change should sharpen our capacity to detect sleeper weeds before they wake up. Uncertainty about future water availability and adequate levels of environmental flows means that a more prudent approach to water allocation would be timely.

RESEARCH (MANAGEMENT WITH MONITORING) NEEDS

How much emphasis we place on these different conservation strategies requires a renewed commitment to carefully targeted long-term research within a framework of management and monitoring. These needs reflect the fact that the consequences of climate change on biodiversity are still very uncertain.

- Existing predictions of the impact of climate change on distribution and abundance have relied largely on bioclimatic models, thereby ignoring the fact that birth, death and movement determine distribution and abundance, not physiology. Research is urgently required on a more process-based understanding of the impact of climate change on spatial population dynamics. Identification of climate change 'refugia', if they exist, and concentration of preventative conservation measures in those areas. Palynological information and climate modelling may enable us to isolate those parts of Australia that have been climatically and ecologically more stable during past colder climates and we need to critically assess whether these are relevant in a warmer world.
- Experimental ecosystem reconstruction is a risky approach to determining the utility of the translocation approach.
- We need research on impacts on marine ecosystems above and beyond coral bleaching by assessing interactive effects of temperature rises, increasing CO_2 concentrations, sediment and nutrient influxes and changes in broad scale oceanic circulation.
- Finally we note our uncertainty about interactive effects. How does climate change interact with existing threats? How much worse will climate change make the impact of over-allocation of rivers, invasive species, vegetation clearance?
- Focus on a longer-term commitment to monitoring key indicators chosen to influence management and policy — e.g. three El Niño cycles at least.

Given the scale of our uncertainty and limited resources we believe that it is worthwhile considering focussed research on:

- mechanisms of how climate change impacts biodiversity;
- a sceptical look at the extent of the impacts and their importance;
- work on short-lived organisms to determine adaptation (we must have a prediction before we start looking for the response);
- a nation-wide, cost-efficient, long-term monitoring program; and
- more work on climate change refugia and introduction of this information into hotspot identification.

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