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Effects of climate change on biodiversity: a review and identification of key research issues

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Abstract. Current knowledge of effects of climate change on biodiversity is briefly reviewed, and results are presented of a survey of biological research groups in the Netherlands, aimed at identifying key research issues in this field. In many areas of the world, biodiversity is being reduced by humankind through changes in land cover and use, pollution, invasions of exotic species and possibly climate change. Assessing the impact of climate change on biodiversity is difficult, because changes occur slowly and effects of climate change interact with other stress factors already imposed on the environment. Research issues identified by Dutch scientists can be grouped into: (i) spatial and temporal distributions of taxa; (ii) migration and dispersal potentials of taxa; (iii) genetic diversity and viability of (meta) populations of species; (iv) physiological tolerance of species; (v) disturbance of functional interactions between species; and (vi) ecosystem processes. Additional research should be done on direct effects of greenhouse gases, and on interactions between effects of climate change and habitat fragmentation. There are still many gaps in our knowledge of effects of climate change on biodiversity. An interdisciplinary research programme could possibly focus only on one or few of the identified research issues, and should generate input data for predictive models based on climate change scenarios.

Key words: biodiversity, climate change, research issues

Introduction

Climate change poses a potential threat to the earth's biodiversity. In comparison to threats by other human-induced environmental changes (e.g., changes in land cover and use (Dale 1997), pollution, effects of increased concentrations of greenhouse gases), direct effects of recent climate change on biodiversity will be slow and difficult to measure, but the processes are global and practically irreversible. Moreover, climate change will exacerbate the stresses already imposed on the environment. For example, in a fragmented landscape, species may be unable to move to a climatically more favorable environment, because their dispersal capacities are insufficient to cross the barriers between the remaining natural areas.

In this paper, current knowledge of effects of climate change on biodiversity are briefly reviewed (Figure 1). In addition, results are presented of a survey of biological research groups in the Netherlands (Van Vuuren and Kappelle 1998), aimed at identifying key research issues for effects of climate change on biodiversity.

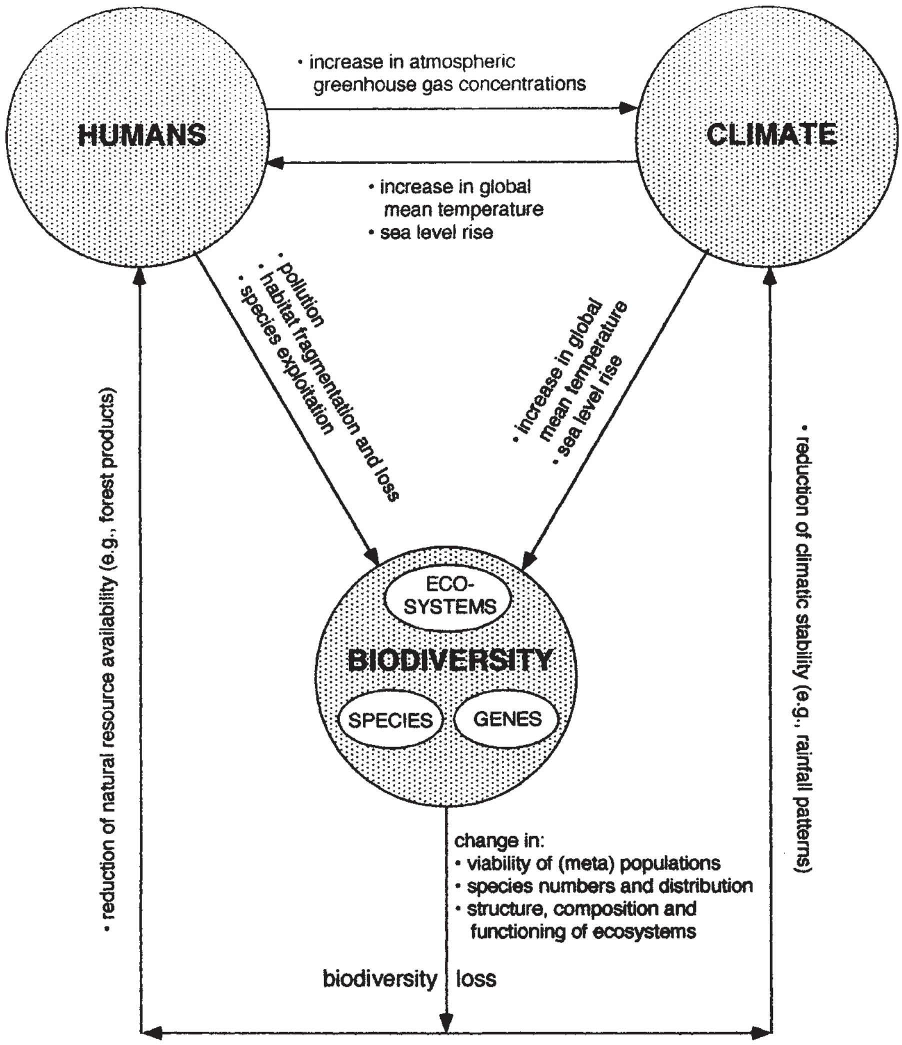

Figure 1. Schematic diagram illustrating the alleged human and climatic forces leading to loss of biodiversity.

Methods

The methodology of this study consisted of: (i) a review of the bibliography on the effects of climate change on biodiversity; and (ii) interviews held in 1997 with ca. 30 biological research groups in the Netherlands, involved in biodiversity and climate change research. Interviews aimed at identifying key issues in research on effects of climate change on biodiversity. Results from the interviews were discussed with participating scientists during a workshop at Leiden University, on 21 November 1997. This workshop contributed strongly in: (a) defining gaps in our knowledge of effects of climate change on biodiversity; and (b) setting priorities among the identified key research issues in this field. Scientists who participated in both the interviews and the workshop suggested a broad range of themes for research. These themes were used to formulate recommendations for a concise two-year research program to be carried out within the Dutch National Research Programme on Global Air Pollution and Climate Change (NRP) at the turn of the millennium.

Results and discussion

Global climate change

Global climate change is one of the most contentious topics in environmentalism, ecology and politics (Houghton et al. 1990, 1992, 1996; Watson et al. 1996; Zwerver et al. 1995). Human-induced increases of atmospheric concentrations of gases such as carbon dioxide, methane, nitrous oxide and chlorofluorocarbons (CFCs) may result in unparalleled increases in global temperature (Houghton 1995; Bush 1997). This would happen through an intensification of the so-called ‘greenhouse effect’ i.e. the absorption of infrared radiation by gases and its re-radiation back toward the surface of the earth. Measurements over the past 130 years show that atmospheric temperatures have already risen considerably and have been the highest in the last few years. A drop in global temperatures in 1992 was caused by the eruption of Mount Pinatubo, a volcano in the Philippines, but this eruption had no lasting effect on trends in global temperature (data from US Department of Commerce).

In 1996, the Intergovernmental Panel on Climate Change (IPCC) issued its Second Assessment Report (Watson et al. 1996), which represents the degree of consensus on various climate change issues. Under the IPCC business-as-usual scenario (i.e. no reduction in carbon dioxide emissions) global environmental change in the next century may include an increase of atmospheric carbon dioxide concentrations from 350 ppmv in 1993 to 525 ppmv in 2050. This may imply a 0.3 °C rise in global mean temperature per decade (Houghton et al. 1992; Sprengers et al. 1994). Recent climate models calculate a potential rise of the global mean surface temperature of about 1 to 3.5 °C by 2100 (Watson et al. 1996). Such a change could be 10 to 50 times faster as the natural average rate of temperature change since the end of the last glaciation (McNeely et al. 1995). However, projected rises in temperature will not be equally distributed over the globe. Mean temperatures at the poles are expected to increase much more (0.8 °C per decade) than those in equatorial regions (0.1 °C per decade). Global mean sea levels are expected to rise ca. 6 cm per decade, thus causing immediate threats (increased salt water intrusion, loss of land and natural resources) to coastal regions.

A rise of global temperatures has been predicted to be accompanied by increased frequency and destructiveness of hurricanes, more protracted droughts, longer and hotter heat waves, more severe rainy periods and significant changes in the area of the great ice sheets of Antarctica (McNeely et al. 1995). However, there appears to be no hard evidence to substantiate all these assertions (Mahlman 1997).

Biodiversity

The word ‘biodiversity’ is a contraction of ‘biological diversity’. Biodiversity has been defined by many scientists and politicians associated with governmental and non-governmental organizations (e.g. McNeely et al. 1990; Groombridge 1992; Wilson 1992; Boyle and Boontawee 1995; Heywood and Watson 1995; Lammerts van Bueren and Duivenvoorden 1996). In their pioneer policy document entitled ‘Conserving the World’s Biological Diversity’ McNeely et al. (1990) consider biological diversity as a concept encompassing all species, plants, animals and micro-organisms and the ecosystems and ecological processes of which they are parts. As they point out, it is an umbrella term for the degree of nature’s variety, including both the number and frequency of ecosystems, species or genes in a given assemblage. The 1992 Convention on Biological Diversity defines biodiversity as ‘the variability among living organisms from all sources, including, *inter alia,* terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part. This includes diversity within species (genetic diversity), between species (species diversity) and of ecosystems (Heywood and Watson 1995).

A recent estimate of the number of species worldwide is 13 million, though only about 1.6 million have actually been described (Heywood and Watson 1995). Certain areas on the globe show exceptional concentrations of species with high levels of endemism and unusually rapid rates of depletion (Myers 1988). These areas are called ‘hot spots’ and are found in certain tropical forests, coral reefs and Mediterranean ecosystems (Myers 1988).

Major threats to biodiversity include habitat alteration and loss, over-harvesting, chemical pollution, invasive species and increasing population pressure. Climate change may modify and enhance local anthropogenic disturbances. According to Jenkins (1992), rates of habitat modification are currently so high that virtually all natural terrestrial habitats and protected areas are destined to become ecological ‘islands’ in surrounding ‘oceans’ of habitat much altered. This process of fragmentation and isolation – main concepts in island biogeographic theory (MacArthur and Wilson 1967) – is predicted to lead directly and indirectly to accelerated species extinctions at both the local and the global scales, thus reducing the world's biodiversity at all levels (Jenkins 1992; Lawton and May 1995). Some authors (Myers 1979, 1989; Ehrlich and Ehrlich 1981) argue that the loss of biodiversity threatens ecosystem integrity, and may ultimately threaten human existence itself.

Effects of paleoclimate change on biodiversity

Understanding the impacts of past climate change on plant and animal life may facilitate the development of models that predict future shifts in species, communities and ecosystems (Webb 1992; Lundqvist 1996; Lowe and Walker 1997). Over the past million years, the most noticeable pattern of global climate variation has been the oscillations between cold and warmer periods (glacials and interglacials), with glacials occurring roughly every 100,000 years. According to Webb (1992) the past 18,000 years BP (Before Present), including the end of the last glacial, are particularly interesting. The rise in global mean temperature of 5 ± 1 °C during this period closely approximates the 4.2 ± 1.2 °C rise that is predicted for the near future, as a result of a doubling of the effective concentration of greenhouse gases (Schlesinger 1989). However, the rate at which the global mean temperature is predicted to rise under future global warming conditions is faster than any natural warming during the past 18,000 years. This implies that many species are likely to be unable to move their ranges rapidly enough to keep up with the changing climate (Webb 1992).

Studies in the Colombian Andes have shown the importance of Pleistocene (2,000,000–10,000 years BP) climate change for environmental and floristic dynamics along elevational gradients in tropical mountain regions (Van der Hammen 1989, 1992; Hooghiemstra and Cleef, 1995). Results depict strong altitudinal shifts in vegetation belts as a response to temperature changes. Palynological research in Costa Rica has revealed a cooling of 7 to 8 °C during the last glacial maximum (Islebe and Hooghiemstra 1997). However, environmental change throughout Central America during the mid Holocene (10,000–0 years BP) seems more affected by changes in humidity than by temperature changes. Dendrochronological studies in Chile and the northern hemisphere show the sensitivity of trees to temperature changes over the last few hundred years (Peters 1992; Szeicz 1997).

Data from Africa stress the impacts of cooler and drier environments on paleotropical rain forest during the last ice age, about 70,000 to 12,000 years BP (Bonnefille et al. 1990; Maley 1996). Fossil pollen records from East African mountains show a descent of vegetation zones indicating a 6 °C change in temperature (Van Zinderen Bakker and Coetzee 1972). As Sosef (1994) points out, the area of lowland rain forest presumably shrank considerably during the last glacial period and ultimately disintegrated into a number of small refuges, situated as islands within an area occupied by more drought resistant vegetation. African shade-loving rain forest species such as those belonging to the genus *Begonia* are presently concentrated within the main postulated refuge localities. They can be regarded as dependable bio-indicators of former refuges (Sosef 1994).

Effects of recent climate change on biodiversity

In this section a number of observations of effects of climate change on biodiversity are described, i.e. (i) shifts of major vegetation zones or biomes, (ii) shifts in ranges of individual species and in the composition of species assemblages, (iii) interactions between effects of climate change and habitat fragmentation and (iv) changes in ecosystem functioning.

(i) Shifts of major vegetation zones or biomes

Changes in global vegetation cover and in the boundaries of the world's biomes are expected to occur in response to global climate change (McNeely et al. 1990; Peters and Lovejoy 1992; Heywood and Watson 1995). As the earth warms, species are generally expected to shift to higher latitudes (poles) and altitudes (peaks). For example, the timber line in Finland would rise about 200 m higher into areas where it used to be during the Atlantic thermal period about 4,500 to 7,500 years ago (Kellomäki 1996). Under projected future global warming conditions, certain areas of endemic and species-rich tropic alpine vegetation may be fully replaced by montane cloud forests presently found at lower altitudes (Halpin 1994).

However, models simulating the displacement of vegetation types or biomes have been criticized for being too simplistic (Leemans 1996; Cramer 1997; Halpin 1997). First, simulated patterns of shifts of biomes as complete entities are not very realistic, because they do not take into account the individual responses of species to changes in climate factors (Leemans 1996). In more recent models, e.g., BIOME (Prentice et al. 1992) plant types show an individualistic response to climate, and new assemblages of plant types can develop in response to climate change. Second, the outcomes of models are often presented as potential vegetation maps based on future equilibrium climates, without an indication of the time required to reach this new stage (Halpin 1997). Third, predictions of poleward and altitudinal movements of species under warmer climates are often based on temperature responses only. When moisture variables are taken into account, the results are far more complex. For example, Halpin (1997) showed that changes in ecoclimatic zonation of mountain areas are generally nonsymmetrical in response, and widely different between latitudes.

(ii) Shifts in ranges of individual species and in the composition of species assemblages

Changes in climate may affect the physiology, phenology and interspecific interactions between individual species, and as a consequence, shifts in geographic distributions may occur. For example, range changes observed for several butterflies in

Britain are ascribed to small temperature increases (less than one degree) during this century (Ford 1982). Similarly, the northward expansion of birch into the Swedish tundra is attributed to warming during the first half of this century (Kullman 1983). However, if affected species are not able to adjust their geographic distribution, their survival chances will be strongly reduced.

In the Netherlands, over the last few decades, 64 vascular plant species have become extinct, while about 84 species have appeared for the first time (Van der Meijden 1993). For many of these 84 'neophytes', the northernmost limit of their geographic range is now in the Dutch delta. Both climate change and direct human influences on ecosystems are assumed to have caused these shifts in species distributions. A study by Nabuurs et al. (1997) reports on the possible effects of climate change on forest ecosystems. Current climate scenarios predict drastic changes in tree species composition in the long term.

Recent shifts in phenology and distribution of a large sample of Microlepidoptera in the Netherlands are also related to climate change (Ellis et al. 1997a, 1997b). During the period from 1975 to 1994, the flight peak shifted on an average to a date 11.6 days earlier, presumably due to the rise in spring temperatures. More than 50% of the species examined had undergone a significant change in distribution over the same period.

Species that are especially sensitive to climate change may be used as indicator species ('bio-indicators') for assessing the climate sensitivity of whole ecosystems. De Groot et al. (1995) describe preliminary results on the selection of bio-indicators, based on six criteria: climate sensitivity, habitat constraints, position within distribution range, dispersal capacity, functional position in the ecosystem and suitability for monitoring. A number of herbaceous plant species, butterflies and birds are identified as suitable bio-indicators for climate change in the Netherlands and Western Europe.

Shifts in geographic distributions of individual species and in the composition of species assemblages can be identified by long-term monitoring studies, using, e.g., Geographic Information Systems (GIS) (Heil and Van Deursen 1996). Natural eco-climatic transitions or ecotones may be especially suitable for monitoring effects of climate change, because they are likely to be especially sensitive to climate change. Examples are tropical tree border lines such as those found at the rainforest–savanna boundary (De Wilde and Van der Maessen 1997) and cloud forest – paramo interface (Cleef 1981; Kappelle et al. 1995) and temperate timber lines such as found in northern Finland (Kellomäki 1996).

Examples of monitoring studies in marine environments are the studies on tropical coral reefs by Bak and Nieuwland (1995), and that on sublittoral communities in the North Sea by De Kluijver (1997). Bak and Nieuwland (1995) monitored permanent quadrates for over two decades and showed a significant decrease in coral colonies, particularly at disturbed shallower reefs. Whereas most of the degradation processes are directly related to human influence, a rise in the temperature of ocean waters will lead to drastic reef degradation in the long run. De Kluijver (1997) characterizes the structure, composition and synecology of a series of sublittoral communities. These communities are expected to change as a consequence of climate change, resulting in a sea level rise, warming of seawater, shifts in seasonal fluctuations and a rise in carbon concentrations.

(iii) Interactions between effects of climate change and habitat fragmentation

Over the past decades, destruction and fragmentation of habitats has led to biodiversity depletion on local, regional and global scales (Harris 1984; Myers 1989). Habitat fragmentation in conjunction with climate change sets the stage for an even larger wave of extinction than previously imagined, based on consideration of human encroachment alone (Myers 1989; Peters and Lovejoy 1992). Habitat fragmentation results in isolation of species populations and may locally lead to a reduction of genetic variation. Fragmentation may also prevent species migration and dispersal towards more suitable habitats in response to climate change (MacArthur and Wilson 1967; Peters and Lovejoy 1992; Bierregaard et al. 1997).

In addition to its effects on migration of populations, fragmentation of landscapes into smaller units can have a large impact on the climate along the edges and inside the remaining fragments. In many forested areas, fragmentation has produced landscapes in which forest edges are a dominant feature and edge influences are extensive in the remaining tracts of the forest (Chen et al. 1993). Saunders et al. (1993) show that rain forest remnants surrounded by cleared agricultural lands are exposed to markedly different solar radiation, wind, water and nutrient regimes than continuously forested regions. Kapos (1989) and Turton and Freiburger (1997) also measure changes in climate along forest interior-edge-exterior gradients in tropical rain forest. Biodiversity may change significantly along these gradients, as is shown for vascular plants along belt transects perpendicular to the edge of cloud forest fragments (Williams-Linera 1990; Oosterhoorn and Kappelle 1999).

In habitat fragments, survival of populations or species that need to adjust their geographic distribution to a changing climate will depend on their migration potential, but also on fragment size, quality and distribution (between-fragment distance, connectivity via corridors), and the character of the matrix surrounding fragments (physical barrier type). Establishing corridors between fragments is an often-suggested management response to changing climate conditions, though much is still unknown about their potential effectiveness. Knowledge is lacking on the required spatial configuration of corridors, e.g., their optimal width, edge to area ratios and orientation in different environments (Halpin 1997).

(iv) Changes in ecosystem functioning

The biogeochemical functioning of an ecosystem depends on the summed, interrelated activities of its organisms, i.e. the ways and rates at which they carry out ecosystem processes (e.g., respiration, carbon dioxide fixation, nitrification, litter decomposition). Climate change may influence ecosystem functioning if the physiology of species is affected, e.g., by changes in temperature or moisture availability. Changes in climate factors may also exceed the physiological tolerance of species and/or disturb their functional relationships with others, causing species to become extinct or migrate to other sites, and probably reducing the ecosystem's biodiversity.

Current losses in biodiversity by human-induced environmental changes has renewed interest in research on the significance of biodiversity for ecosystem functioning and resilience with respect to stress and disturbance (Naeem et al. 1994; De Ruiter et al. 1995; Folke et al. 1996; Mooney et al. 1996; Brussaard et al. 1997; Chapin et al. 1997; Díaz and Cabido 1997; Hooper and Vitousek 1997; Tilman et al. 1996, 1997; Wardle et al. 1997). In his commentary on recent outcomes of field experiments (Hooper and Vitousek 1997; Tilman et al. 1997; Wardle et al. 1997), Grime (1997) concludes that there is currently no convincing evidence that ecosystem processes are crucially dependent on higher biodiversity. Rather, the functional characteristics of the dominant plant species would be important in controlling ecosystem processes.

However, it remains obvious that losses of species or functional groups from an ecosystem could at some point impair its functioning and its capacity to provide services to society (Mooney et al. 1996; Chapin et al. 1997; Grime 1997). Some species or functional groups carry out unique functions and cannot be substituted by others. But also the loss of species with similar ecosystem effects may reduce ecosystem resilience and narrow the options for adjustments to climate change.

Identification of key research issues

(a) Interviews with research groups in the Netherlands

During interviews with ca. 30 biological research groups in the Netherlands, research suggestions were made for conducting studies on effects of climate change on biodiversity. These suggestions can be grouped into the following six key research issues:

(i) Spatial and temporal distributions of taxa. This type of research seeks correlations between long-term data on distributions of taxa and long-term climate data within an area. By reconstructing past changes, potential future changes in the distributions of taxa under climate change scenarios may be understood. Different sources of information (field records, specimens from systematic collections, fossils) may be used, depending on the time scale at which the research is undertaken.

(ii) Migration and dispersal potentials of taxa. Autecological research on a number of plant and/or animal species (possibly representing functional groups of species) may answer the following questions: How fast can species migrate in response to climate change? What are their chances for survival and establishment in new habitats? and, what are the consequences of species migration for biodiversity in the abandoned and the newly colonized habitats?

(iii) Genetic diversity and viability of (meta)populations of species (including research on the effects of habitat fragmentation). Climate change may result in isolation of populations within a species, putting constraints on the maintenance of genetic diversity, with the ultimate risk of extinction. Measurements of the genetic diversity within a selected metapopulation will enable an assessment of the degree of reproductive isolation and the viability of local populations, as well as the consequences for the genetic diversity of the metapopulation in the long term.

(iv) Physiological tolerance of species. Changes in temperature or moisture availability will affect physiological processes in plants and animals. In addition, the phenology of many organisms, i.e. the timing of different phases in their life cycles, will be affected (e.g. the onset and duration of winter rest). Changes in climate factors and their seasonal patterns, and the magnitude and timing of extreme values are important. Assessment of species' tolerance for changes in climate factors will enable assessment of the risks posed by climate change for the survival of those species. This is especially relevant for (rare) species that do not have a high dispersal or migratory capacity.

(v) Disturbance of functional interactions between species. Species are affected in different ways by climate change, implying that functional interactions between species will be affected. The consequences may be positive or negative for the survival of individuals of either or both species (and possibly others). Numerous examples of species interactions can be given, e.g. between plants and herbivores, between predators and preys, etc. Special cases of disturbances of functional interactions between species involve 'displacements' in time and/or space, which are often caused by phenological changes.

(vi) Ecosystem processes (including research on the direct effects of increased concentrations of greenhouse gases such as carbon dioxide). Climate change may affect the physiology, phenology and interspecific interactions of individual species and the species composition of ecosystems. All these responses can have consequences for ecosystem processes, e.g., primary production, food web relations, and nutrient cycling. In turn, changes in ecosystem processes have complex feedback effects on the functioning of species, species composition and possibly climate (e.g., increased production of carbon dioxide after warming and drying of tundra ecosystems). Assessments of long-term consequences of changes in ecosystem processes will require experimental work as well as the development of simulation models.

(b) Recommendations for an NRP research programme

The results of the interviews were used to formulate recommendations for a 2-year research programme to be carried out within the Dutch National Research Programme on Global Air Pollution and Climate Change (NRP). It was recommended to focus the NRP programme on two questions, i.e.:

(1) What are the effects of current and potential climate change on spatial and temporal distribution patterns and on the existence of species and ecosystems?

(2) What biological mechanisms are involved in the responses of species and ecosystems to global climate change?

In addition, two complementary approaches were recommended, i.e.:

(i) Analyses of long-term data sets comprising biogeographical and climate observations and measurements;

(ii) Experimental work on a number of species or functional groups of species aimed at investigating their physiological or phenological responses to climate change, and their migration or dispersal potential.

The emphasis of the NRP programme was put on research in the Netherlands and north western Europe, although it was realized that a major effort is needed to monitor and predict the effects of climate change in the tropics. Research priorities for the tropics will depend on the state of knowledge of genetic, taxic and ecosystem diversity for a given region.

Concluding remarks

Assessing the impact of climate change on biodiversity is difficult, due to the spatial and temporal scale and the complexity of the problem, and its interactions with other environmental factors. This is illustrated by the broad range of research issues identified in this paper. Recommendations for the research programme mentioned above were based on these issues, but also directed by budgetary and time constraints of the specific programme. Hence, another approach may be taken under different circumstances. However, a research programme should be interdisciplinary, and generate input data for predictive models based on climate change scenarios.

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