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OECD Workshop on the Benefits of Climate Policy:
Improving Information for Policy Makers

Analysing changes in ecosystems for different levels of climate change

by Rik Leemans and Bas Eickhout

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FOREWORD

This paper was prepared for an OECD Workshop on the *Benefits of Climate Policy: Improving Information for Policy Makers*, held 12-13 December 2002. The aim of the Workshop and the underlying Project is to outline a conceptual framework to estimate the benefits of climate change policies, and to help organise information on this topic for policy makers. The Workshop covered both adaptation and mitigation policies, and related to different spatial and temporal scales for decision-making. However, particular emphasis was placed on understanding global benefits at different levels of mitigation -- in other words, on the incremental benefit of going from one level of climate change to another. Participants were also asked to identify gaps in existing information and to recommend areas for improvement, including topics requiring further policy-related research and testing. The Workshop brought representatives from governments together with researchers from a range of disciplines to address these issues. Further background on the workshop, its agenda and participants, can be found on the internet at: www.oecd.org/env/cc

The overall Project is overseen by the OECD Working Party on Global and Structural Policy (Environment Policy Committee). The Secretariat would like to thank the governments of Canada, Germany and the United States for providing extra-budgetary financial support for the work.

This paper is issued as an authored "working paper" -- one of a series emerging from the Project. The ideas expressed in the paper are those of the author alone and do not necessarily represent the views of the OECD or its Member Countries.

As a working paper, this document has received only limited peer review. Some authors will be further refining their papers, either to eventually appear in the peer-reviewed academic literature, or to become part of a forthcoming OECD publication on this Project. The objective of placing these papers on the internet at this stage is to widely disseminate the ideas contained in them, with a view toward facilitating the review process.

Any comments on the paper may be sent directly to the authors at:

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1.   INTRODUCTION

Climate and weather directly control the distribution and productivity of species, ecosystems and biomes. Each climate zone is characterised by their typical ecosystems. The early explorers already knew this. They described climate on the basis of vegetation observations and vice versa. This relationship was also used to develop climate-classification models that describe ecosystem[1] patterns (e.g. Cramer and Leemans, 1993). Similar patterns can be distinguished in the marine ecosystems (Pauly and Christensen, 1995).

Large-scale ecosystem patterns are strongly influenced by climate and will continue to change with climate change. Such historical changes have been reconstructed on basis of pollen deposits, tree rings and other means (e.g. Huntley and Webb, 1988). These studies have shown that in the past, on a millennium time scale vegetation has been in close equilibrium with climate on most continents. On smaller temporal and spatial scales, however, the dominant role of climate is reduced. Here local differences in soil, terrain and hydrological properties define the occurrence of species and ecosystems, while heterogeneous landscapes results from time lags due to ecological succession and disturbances. Furthermore, over the last several thousand years humans have managed species, ecosystems and landscapes to obtain specific goods and services from ecosystems (Daily *et al.*, 1997). Humans currently dominate most ecosystems.

Climate change will influence ecosystem patterns on all different scales. Emanuel *et al.* (1985), who used the Holdrige life-form approach, showed that climate change would have large impacts on the distribution of ecosystems. They concluded that about 45% of all the world's ecosystems would change under a doubled-CO_2 climate. Their pioneering result can still be compared with recent studies with more advanced models. Of course, the more recent studies have added more spatial detail, used dynamic models, more realistic species and ecosystem responses, and more comprehensive climate scenarios, but the magnitude of change of recent studies is still very similar to the earlier ones.

Here we will evaluate climate change impacts on ecosystems and try to relate them to a single, widely used climate change indicator: global mean temperature increase (c.f. Smith *et al.*, 2001). Doing this we will try to further quantify the type of change (positive, neutral or negative). The shifts will further be quantified for each specific ecosystem so that also regional aspects are highlighted. We will do this for several climate-change patterns obtained from General Circulation Models (GCMs), normalised for 1, 2 and 3 $^{\circ}$C in global mean temperature increase, in order to address some of the major uncertainties in regional patterns.

These large-scale impacts on species, landscapes, ecosystems and the services they provide (e.g. water purification, slope stabilisation, carbon sequestration and many cultural and esthetical values) are mostly non-market impacts. Even though the value of many ecosystem services (e.g. crops and timber) and other aspects of ecosystems can be estimated in dollars (e.g. Balmford *et al.*, 2002), we believe that the actual damages or benefits of changes in the diversity of species, ecosystems and landscapes are not

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[1] We use the term 'ecosystems' in a very broad sense here and synonymous with large-scale vegetation patterns or biomes.

satisfactorily characterised in monetary terms. This is because many important aspects of ecosystems are then trivialised or marginalized by selecting inappropriate discount rates that neglect unique features and irreversible impacts. Therefore we only present the first order impacts based the actual simulated shifts in ecosystems. We will not explicitly focus on the impacts of sea-level rise because many other studies have already addressed this. For example, Gitay *et al.* (2002) state that by the end of this century 20% of the coastal wetlands could be lost due to sea level rise. This impact is of the same magnitude as the impacts on terrestrial ecosystems, so we assume that our terrestrial-based figures will be representative for all ecosystems.

Aiming to explore changes in ecosystems at different levels of climate change, this paper is organised as follows. We first give a short literature overview of different impacts of climate change on ecosystems. This review highlights that many of the impacts projected in the impact literature are already unfolding on land, on mountains and along the coasts. Second, we will shortly describe the IMAGE model (Alcamo *et al.*, 1998) and its scenarios (IMAGE team, 2001a,b) that we have used to calculate the impacts of climate change. Additionally, we will evaluate different interpretations of these results.

By using just the global-mean-temperature-increase (GMTI) indicator, realistic dynamic aspects of the response are neglected. If a $2^{\circ}C$ increase occurs over 1000 years (i.e. 0.02 $^{\circ}C$ per decade), most affected ecosystems can probably adapt, while when it happens over 50 years (i.e. 0.4 $^{\circ}C$ GMTI per decade) most ecosystems will probably rapidly deteriorate. The rate of change (or the period over which the change lasts) is important for defining the actual impact. To analyse some the consequences of different rates of change, we further assessed how ecosystems respond to different GMTI in 2100. This approach represents different rates of temperature change. Such criteria is unambiguously linked to the objective of the Framework Convention of Climate Change, which states that atmospheric concentrations must be stabilised as such a level that ecosystems can naturally adapt.

2.   REVIEW OF ECOSYSTEMS IMPACTS

Most impact studies on ecosystems have used climate classifications (e.g. Cramer and Leemans, 1993; Malcolm and Markham, 2000), which depicted large-scale vegetation shifts as a consequence of climate change. Few have looked at the transient impact of climate change. Generally, decline is a fast process (weeks to years), while succession is several magnitudes slower (decades to millennia). Solomon and Leemans (1997) concluded that future climate change could lead to large-scale synchronisation of disturbance regimes, leading to the emergence of early-phase successional vegetation with opportunistic generalist species (i.e. weed species) dominating over large areas and a decline in precious, slow growing rare species.

Impacts of climate change are already long apparent for glaciologists (Street and Melnikov, 1990). They have well-calibrated observation records of retreating glaciers and accompanying ecosystems all around the world. Currently 90% of all glaciers are retreating and the increasing ones (e.g. southern Norway and Antarctica) are due to increased precipitation. Changes in the mass balance of glaciers are the result of addition through precipitation and decline through melting (Oerlemans *et al.*, 1998). Recently, a long-term record from Mount Kilimanjaro was released, which also showed this typical trend (Thompson *et al.*, 2002). They extrapolated the trend and concluded that this last African tropical glacier will be gone in 2015. Such changes in glaciers will have pronounced consequences for tourism and hydrology. Also other cold-temperature related phenomena, such as permafrost are disappearing all around the world (Jorgenson *et al.*, 2001). This will reduce soil stability, which has far-reaching consequences for infrastructure and slope stability.

Grabherr *et al.* (1994) were the first to highlight that ecosystems are already changing because of climate change. They used long-term observations from alpine vegetation and unambiguously demonstrated that the distributions of many species had increased in altitude. Since then many observation of the impacts of climate change have been made (Root *et al.*, 2003). Some covered large areas such as the earlier onset of the growing season over the Northern Hemisphere (Myneni *et al.*, 1997). Sometimes the observations related to complex interactions. Both and Visser (2001), for example, analysed a long-term dataset of feeding, nesting, laying dates and breeding success of the migratory Flycatcher and the overwintering Great Tit in the Netherlands. Both species have advanced their egg-laying date over the past 20 years by weeks. The required temporal shift has been insufficient for the flycatcher, due its arrival date, which has not advanced because their departure from Africa is determined by daylength. Nowadays, Flycatchers immediately start egg laying without a necessary recovery period. This reduces their breeding success and favours the Great Tit.

Recently a detailed systematic study on lichen distribution was published (van Herk *et al.*, 2002). Most lichens species are extremely sensitive to acidification and decreased in the sixties. These species are a good indicator of ecosystem vigour and, hence, lichen species have been systematically sampled and monitored since the early seventies in The Netherlands. This monitoring network now also produces useful insights into climate change impacts, especially because lichens have no dispersal delays. When environmental conditions become appropriate, they spread rapidly. Sampling has shown that in the nineties, many species increased in abundance, highlighting the effectiveness of the European acidification policies. Since 1995, however, boreal species, which have their southern limit in The Netherlands, slowly disappeared, while several subtropical and even a few tropical species appeared, none of which were

previously recorded in the Netherlands. These shifts agree with expected ecosystem shifts but illustrate the fact that free habitats (i.e. locations with the appropriate conditions for that species) are required for an adequate establishment of new species. Most other plant and animal species disperse much slower, have narrow habitat requirements and have long live cycles (e.g. trees) and once established could occupy a habitat even when if environment has become less favourable. These limitations reduce the dispersal and thus the adaptability of many species. This notion is consistent with IPCC (Gitay *et al.*, 2002), which states that the frequency, intensity, and location of disturbances will affect, whether, how and at which rate existing ecosystems will be replaced by new plant and animal communities.

Gitay *et al.* (2002) have comprehensively assessed the impacts of climate change on biodiversity. They emphasised both that in periods of rapid climate change, already vulnerable species will become more vulnerable and extinction rates increase. Species with small ranges, restricted habitat requirements and slow dispersion strategies will decline. For example, Europe has experienced more periods with rapid climate change over the last 20.000 years than North America. This could explain the generally lower levels of tree species diversity in Europe, when compared with North America. They conclude that climate change will affect all aspects of biodiversity but the changes have to consider the impacts from past, present and future human activities, such as land use and increased CO_2 concentrations.

Of course, climate change is not the only influence on ecosystems. Many other changes, such as nitrogen deposition, land-use change, invasive species, increasing CO_2 concentrations and ozone alter ecosystems. Although regionally the impacts could strongly differ (Sala *et al.*, 2000; Leemans, 1999), all these environmental changes increase stress on species, ecosystems and ecosystem services.

3.   METHODOLOGY

All assessments currently point to significant impacts of climate change on ecosystems even at smaller levels of climate change. This has resulted in incorporating different ecosystem models in integrated assessment models that simulate the causal chain of emissions, concentration, climate change, impacts and responses. These models generate comprehensive scenarios of human activities (energy use, land use and industrial activities) and the consequent emissions. Nowadays the most widely used set of scenarios in climate change impact assessment is the set of SRES scenarios (Nakícenovíc *et al.*, 2000). Here we have used the IMAGE model and their implementation of these scenarios (Alcamo *et al.*, 1998; IMAGE team, 2001a,b). This section presents some aspects of IMAGE that are relevant for assessing the impacts on ecosystems.

The terrestrial vegetation, land-use and carbon (C) models in IMAGE 2 have been developed to simulate the consequences of changes in atmospheric CO_2 concentrations and climate on natural vegetation patterns, land use, land cover and the terrestrial C cycle. The terrestrial C cycle is an important determinant of the build-up of atmospheric CO_2 concentrations on an annual to century time scale. It also involves many feedbacks with the climate system and land-use change. These models are implemented on a 0.5^o longitude and latitude grid covering all current areas with terrestrial ecosystems. Each cell is characterised by its current climate (temperature, precipitation and cloudiness), land cover, terrain and soil. Climate change is obtained through the standardised IPCC pattern scaling approach (Carter *et al.*, 2001) combining the calculated global mean temperature increase with a normalised pattern of climate change from a climate model. This results in a spatially explicit pattern of climate change, which is combined with current climate to obtain future climate. We have used several climate models to analyses the uncertainty stemming from different climate-change patterns (IMAGE team, 2001b).

The terrestrial vegetation model computes the potential distribution of natural vegetation. The calculation procedure is straightforward. First, a series of relevant climate indices is calculated, including frost occurrence and severity, characteristics of the growing season, and moisture availability. Ranges of these indices are then used by the BIOME model (Prentice *et al.*, 1992) to determine the distribution of major plant types (e.g. evergreen coniferous trees, drought deciduous trees, desert plants). The plant types are combined into ecosystems that describe the natural vegetation patterns. As temperature and moisture patterns change, computed ecosystem patterns shift. BIOME only calculates an instantaneous *equilibrium* response to climate change by shifting potential natural ecosystem patterns. Such shift, however, takes time and could not occur immediately due to the lack of better-adapted plant types in the surroundings. This results in lags in the vegetation response.

The Terrestrial Carbon model simulates the C fluxes between the terrestrial biosphere and the atmosphere. The major processes determining the terrestrial C cycle are photosynthesis and respiration. Photosynthesis results in the assimilation of C into plant tissue. The net C uptake by plants (i.e. Net Primary Productivity, NPP) is allocated to different plant tissues. These allocation patterns, which are ecosystem specific, further differentiate the terrestrial C cycle. Every plant compartment has a specific turn-over time after which most of the C becomes part of the organic C pools in the soil (Klein Goldewijk *et al.*, 1994). Soil respiration releases C and thus results in a C flux from the biosphere to the atmosphere. The net C sequestration or productivity of an ecosystem is expressed as Net Ecosystem Productivity (NEP), which is the difference between the annual NPP-fluxes and soil respiration rates. The different

lifetimes of C in plant and soil compartments, the influence of CO_2 concentrations, climate and other factors on NPP and respiration rates, and the vegetation response to climate change in composition and succession, highlight the complexity of terrestrial C cycle. The calculation of NEP and thus the terrestrial C-flux strongly depends on the interactions of all these factors.

The model automatically calculates the effects of land-cover transitions, and changes in atmospheric CO_2 concentrations and climate on NPP and NEP. When natural vegetation becomes agricultural land the C stored in the original vegetation is released. When agricultural land is abandoned or becomes unsuitable under climate change, the natural vegetation, which is always kept in the background of an agricultural land cover type, emerges again. Also after timber extraction the carbon in the vegetation is adjusted. Vegetation shifts from one natural vegetation towards another due to climate and CO_2 concentration change is a difficult transition to handle with respect to C dynamics. Empirical evidence for these vegetation responses is only available from long-term paleo studies (e.g. Huntley and Webb, 1988) and these could well be irrelevant for defining vegetation response to rapid climate change over the next centuries. This is the time scale that we address in IMAGE 2. Since NPP and NEP will probably not be in equilibrium during such vegetation conversion, we have implemented a lagged response using a linear interpolation, which parameterises different vegetation transitions between original and new vegetation types.

If the conversion only involves the disappearance of BIOME's plant types from a land cover type, transitions could happen rapidly; if plant types have to enter a region the transition should be much slower. Grasses and shrubs probably disperse more rapidly than long-lived species, such as trees. The speed of these transitions is thus not only depending on the plant and land-cover types involved but also on the distance from seed sources. Unfortunately, little data and theory is available on this issue. Some authors have argued that rapid climate change could result in a large and immediate C flux to the atmosphere because of the large-scale decline of vegetation types (Smith and Shugart, 1993). We believe that such response is exaggerated. We therefore have developed an approach based on the assumptions that new individuals of better adapted plant types will enter a new region eventually. This migration process is modelled as a function of distance, migration rates and original and new vegetation types, where the function alters the actual land-cover type, NPP and NEP (van Minnen *et al.*, 2000). The processes involved are strongly influenced by the rate of climate change, the total extent of vegetation at risk and the possibility for natural land-cover types to adapt to new conditions.

We have used the SRES scenarios as implemented by (IMAGE team 2001a,b). These scenarios are based on different narratives (Nakícenovíc *et al.*, 2000) that depict different plausible future worlds. It goes beyond the scope of this paper to describe these scenarios. All the data is available from CD-rom (IMAGE team; IMAGE team (2001a,b). The emission figures are listed in the original SRES report (Nakícenovíc *et al.*, 2000), while detailed land-use emissions are presented in Strengers *et al.* (2003). A detailed sensitivity analysis was developed to address some of the uncertainties that stem from feedbacks in vegetation response, land use change and the carbon cycle. The findings of this analysis stressed the importance of C-cycle feedbacks in determining the final atmospheric CO_2 concentration and thus climate change. The most important processes included the climate sensitivity (the amount of climate change at doubled CO_2 concentrations), CO_2-fertilisation (enhancement of plant growth at higher CO_2 concentrations) and soil respiration (release of soil carbon though decomposition).

We have used several SRES scenarios to be able to use different GMTIs. For illustration purposes we limited ourselves to a range of GMTIs in 2100 of 1, 2 and 3 $^{\circ}$C respectively. This is consistent with the IPCC approach by Smith *et al.* (2001) and corresponds to a range of 0.1 $^{\circ}$C to 0.3 $^{\circ}$C per decade. Because the GCM-pattern scaling approach (c.f. Carter *et al.*, 2001) is used in IMAGE, total ecosystem impacts can easily be estimated for these temperature increase levels.

3.1 Climate and Impact indicators

The indicators that we used for this paper are all relatively simple and straightforward. First, we relate the impact levels to global mean annual temperature change as calculated by the IMAGE model. This temperature increase is related to the regional patterns of temperature and precipitation change. For impacts, this is important, because changes in moisture availability lead in many regions to larger impacts than just temperature change. However, the highest temperature increases are found in the high latitude regions, where ecosystems are also temperature limited. The use of different GCMs lead to different regional patterns in temperature and precipitation change. This is still one of the major uncertainties in impact assessment. Therefore we have used and compared the patterns of different GCMs for this analysis. Different emission scenarios show different temporal development of the impacts, while the different GCM patterns shows different regional patterns.

Another climate related indicator is the rate of global mean temperature change. This indicator is helpful to estimate the adaptive capacity of ecosystems. Among the first to use this indicator were Vellinga and Swart (1991). They arbitrarily defined a threshold on 0.1 ^{o}C per decade (i.e. 1°C per century) under which most ecosystems could adapt. Therefore, this indicator was also used to define 'safe' emission levels (e.g. the safe landing approach: Alcamo and Kreileman, 1996; and the tolerable windows approach Petschel-Held *et al.*, 1999). Swart *et al.* (1998) have used results from the vegetation migration and adaptation routine of IMAGE to show that vegetation types like grass and desert can adapt quickly to climate change. Forest ecosystems, however, have more difficulties to adapt to climate change. From these ecosystems, Swart *et al.* (1998) deduced that only at a rate of change of less than 0.05 ^{o}C per decade could most forested ecosystems adapt to the climate changes simulated during the 21st century. This coincides with stringent emission reductions worldwide. In this study, we estimate the rate of change on basis of the global mean temperature in 2100, e.g. a 1 ^{o}C temperature increase in 2100 coincides thus with an average 0.1 ^{o}C per decade, 2 ℃ averages 0.2 ℃ per decade and so on.

The major impact indicator that we use is shifts in ecosystems. IMAGE projects changes in ecosystems by checking the climatic envelopes of different plant types that occur in the region. Climate warming leads to a polewards or upwards shift in many ecosystems. We have calculated for each ecosystem the current and future extent (in km^2). These shifts are, however, more complex than just changes in net extent. In some regions, an ecosystem is reduced, while in other regions this ecosystem actually expands. We therefore use four different indicators to fully describe the shifts. First is the net change in extent. This change can be positive (an overall increase in extent) or negative (a overall decrease in extent) and results from the net effect of reductions and expansions world-wide . Second is the stable area, which indicate the ecosystems that do not change. The third is the actual reduction in extent. Here only the disappearance of an ecosystem is listed. The last indicator is the actual increase in extent, listing the expansion of an ecosystem. This gives an indication of the future area into which species have to disperse. The original area of an ecosystem is the reduction in extent plus the stable area, while the future area is the stable area plus the increase in extent. The data is both available in absolute terms (change in area) and relative terms (percentage change relative to the extent in 1990). All these changes are calculated for 1, 2 and 3 ^{o}C (Figure 1).

Not all changes are alike. Some of the changes are positive. These shifts are generally characterised by shifts from deserts to grasslands and from grasslands to forests. Here NEP of an ecosystem increases and there are more opportunities to use the ecosystem. Neutral changes are those where ecosystems are replaced by similar ecosystems. Negative changes are those that depict a decline in use opportunities and a release of carbon. Often these changes are triggered by decrease in moisture availability (precipitation minus evapotranspiration). Table 1 defines all these changes generically.

Figure 1. Shifts in ecosystems for a global mean temperature increase of 3 °C and the HADCM climate change patterns.
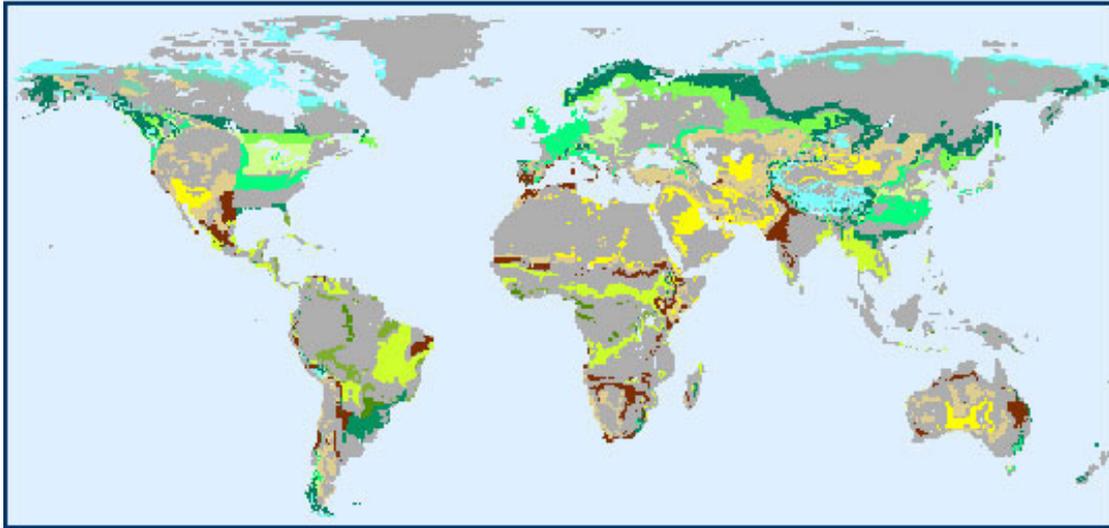

Table 1. Definition of positive (green or +), neutral (beige or O) and negative (red or -) shifts in ecosystems. We always compare the shift to current (i.e. 1990) vegetation

Original vegetation / New vegetation	Ice	Tundra	Wooded tundra	Boreal forest	Cool coniferous forest	Temperate mixed forest	Temperate deciduous	Warm mixed forest	Grassland and steppe	Hot desert	Scrubland	Savannas	Tropical woodland	Tropical forest
Ice	O	-	-	-	-	-	-	-	-	-	-	-	-	-
Tundra	+	O	-	-	-	-	-	-	-	-	-	-	-	-
Wooded tundra	+	+	O	-	-	-	-	-	0	+	O	-	-	-
Boreal forest	+	+	+	O	-	-	-	-	+	+	+	+	-	-
Cool coniferous forest	+	+	+	O	O	-	-	-	+	+	+	+	-	-
Temperate mixed forest	+	+	+	O	O	O	O	-	+	+	+	+	-	-
Temperate deciduous forest	+	+	+	O	O	O	O	-	+	+	+	+	-	-
Warm mixed forest	+	+	+	O	O	O	O	O	+	+	+	+	-	-
Grassland and steppe	+	O	-	-	-	-	-	-	O	+	-	-	-	-
Hot desert	O	-	-	-	-	-	-	-	-	O	-	-	-	-
Scrubland	+	+	O	-	-	-	-	-	O	+	O	-	-	-
Savannas	+	+	+	-	-	-	-	-	+	+	+	O	-	-
Tropical woodland	+	+	+	+	+	+	+	+	+	+	+	+	O	-
Tropical forest	+	+	+	+	+	+	+	+	+	+	+	+	+	O

Although some of the changes are definitely positive from the perspective of human use, they are not positive from all perspectives. Many ecosystem impacts involve reductions in biodiversity. Humans now use 40% of all land. In such landscapes there is little room for large patches of natural vegetation, where typical successional and disturbance patterns can develop. In these landscapes, we have created nature reserves to prevent unique species and ecosystems from going extinct. Although current efforts are trying to connect reserves to increase their resilience, such networks are still inadequate to preserve all the habitats for most important species. Species continue to go extinct.

In Johannesburg, the World Summit on Sustainable Development defined as a target a significant reduction in species extinction and once more emphasised the importance of nature reserves (WSSD, 2002). Leemans and Halpin (1992) were the first to use the shifting of ecosystems in large nature reserves as a proximate indicator for changes in biodiversity. The rationale was that when the current vegetation disappears it is highly unlikely that the original protection objectives can still be met. Such nature reserves are therefore of no conservation value, even if the underlying shift (Table 1) is potentially positive. The indicator is percentage of impacted nature reserves and is calculated by IMAGE using a comprehensive database on the locations of large nature reserves (i.e. > 2500 ha). These locations are overlaid with the shifting ecosystems.

4. RESULTS

The shifts in ecosystems show that even with a small climate change the impacts on terrestrial ecosystems are pronounced (Figure 2 and Appendix 1). A 1 $^{\circ}$C warming alters more than 10% of all ecosystems (global average 10.4%; range for the different GCMs 10.2% – 10.5%). This means that on average 89.6% of all ecosystems are stable. However, there are large differences in specific ecosystems. The most stable ecosystems (i.e. more than 96% stable area) are unfortunately the ecosystems with little vegetation (hot desert and ice). The largest changes are in the wooded tundra regions (only 53% stable) and cool conifer forests (only 77% stable). There are regional differences between the GCMs, but overall the changes are reasonably small (see GCM ranges in Appendix 1). Similar magnitudes in impacts emerge for all the different GCMs.

These ecosystem impacts increase with increasing temperatures. At 2°C and 3 $^{\circ}$C only 84% and 78% of all terrestrial ecosystems are stable, respectively. The globally aggregated figures for all GCMs are very similar. The largest regional differences (> 15% difference in regional patterns) are in the tundra, wooded tundra and cool conifer forests. These findings are similar to those of Malcolm and Markham (2000), who strongly emphasised the large impacts on tundras. Overall the simulated magnitudes of impacts in IMAGE seem to be lower than in similar assessments (e.g. Emanuel *et al.*, 1985; Cramer and Leemans, 1993; and Malcolm and Markham, 2000). This is probably due to some of the feedback processes, such as increased water use efficiency at higher CO_2 concentrations that are included in IMAGE 2.

Current tropical forests and woodlands are relatively stable across the 1 to 3°C GMTI range (95,3 to 91,4% respectively of its current extent remains stable). The decline is caused by an increase in moisture deficit. The magnitude is different from the findings of Cox *et al.* (2000), where most forests in the Amazon rapidly decline. Their vegetation model, however, is very drought sensitive and linked to a GCM that unrealistically reduces precipitation over the Amazon. In IMAGE some of the drought related impacts are also neutralised by the enhanced water use efficiency under higher CO2 concentrations. Additionally, in some years, the forests are more vulnerable. An example of this was the severe El Niño in 1997, which reduced precipitation over large parts of Indonesia and Africa, resulting in many forest fires (Page et al., 2002). The vulnerability of these forests is thus not a mere function of the climate-change trend, but more of changes in precipitation variability. These aspects seem real but are not simulated by IMAGE 2.

The temperate and boreal forests show larger shifts. Only 50,1% – 86,9% of these ecosystems are stable with a 3 $^{\circ}$C GMTI. Especially the cool conifer forests (e.g. Black Forest in Germany; Hemlock forests in the Pacific Northwest) decline strongly in their current location. Boreal forests replace large parts of the southern edges of the tundra and temperate forests replace boreal forests (see Figure 2). Worldwide there is, however, an increase in temperate forests.

The wooded tundra is strongly reduced in extent, because boreal forests replace it. On average only 27% (range 23% – 32%) of the original ecosystems remain in place with a 3 $^{\circ}$C GMTI. Even with a modest 1 $^{\circ}$C only 53% (range 52% – 54%) remain stable. Here is the largest risk for accelerated species extinctions, which will have its impact on other regions because several migratory bird species use this ecosystem as their breeding grounds. This ecosystem is also dominated by wetlands. The RAMSAR and Biodiversity conventions are surely not served with such immense decline in wooded tundra areas.

Figure 2. Different changes in extent of ecosystems for a temperature increase of 1 ^{o}C (top), 2 ^{o}C (middle) and 3 ^{o}C (bottom).
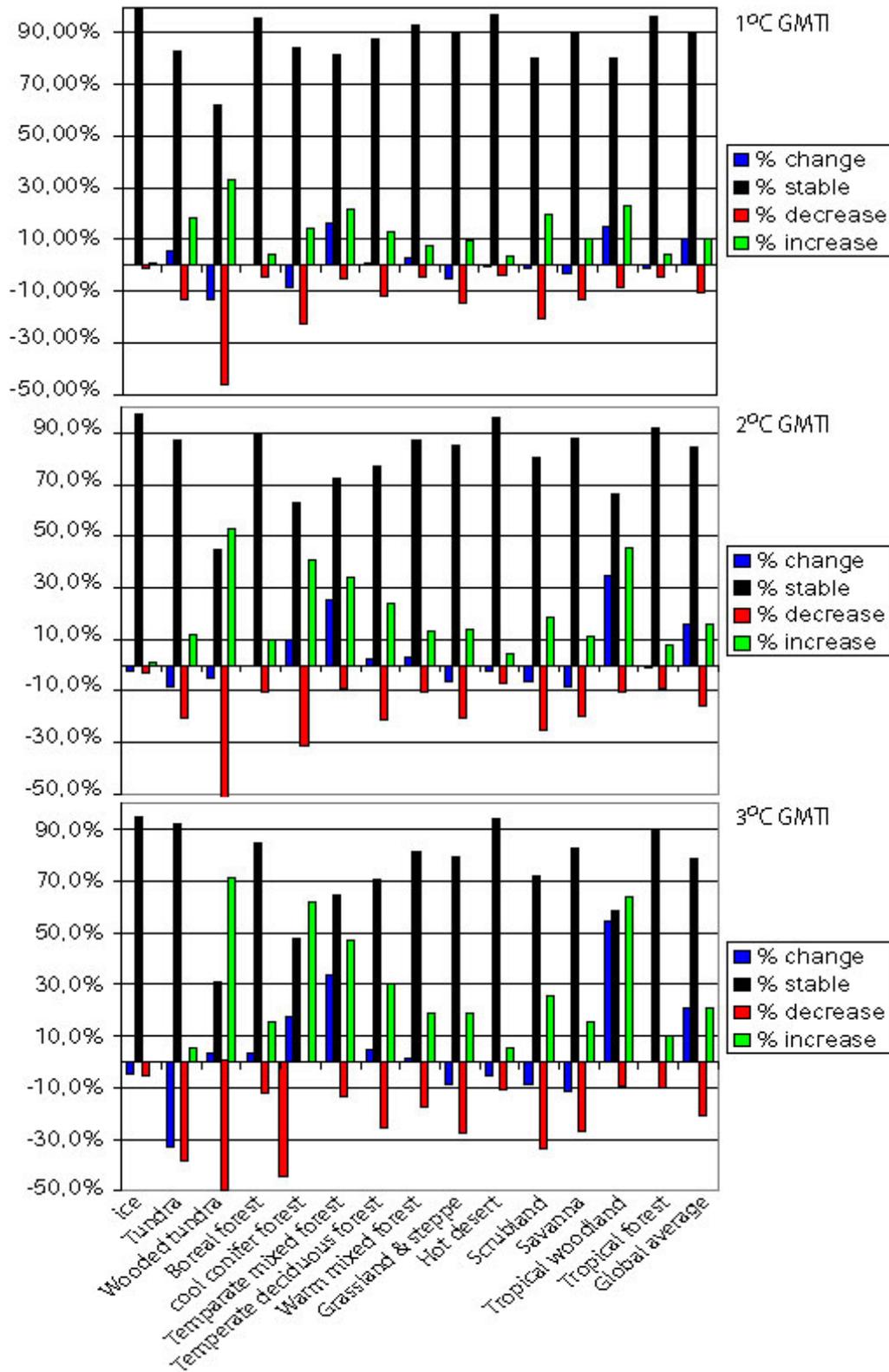
Globally 21,9% (range 21.1% – 23.5%) of all ecosystems will change with a temperature increase of 3 °C. This amount is reduced at 2 and 1 °C GMTI but does not disappear . The average changes are 15.9 % (range 15.5% and 16.3%) for 2 °C and 10.4% (range 10.2% and 10.5%) for 1 ℃ GMTI. The magnitude of the impacts rapidly increases initially declining with GMTIs. However, although the average decline in individual ecosystems is of a similar magnitude,, the ranges are much larger (i.e. 7.0% – 74% for 3 °C, for 5.0% – 66% for 2 °C and 2 % – 47% for 1 °C). The ranges of expansion in individual ecosystems are of similar magnitude. This shows that a global aggregation easily can underestimate the actual impacts on ecosystems.

The analysis of the type of change (Table 1) provides some different insights. Globally (Figure 3) the results show that positive and neutral impacts increase with climatic warming, while negative impacts decrease. Initially the positive and negative impacts balance each other approximately. The vegetation driven changes in the ecosystems "ice", tundra, and hot desert are per definition positive, while changes in tropical forests are per definition negative. In the tropical ecosystems (scrubland, savannahs and woodlands) positive impacts increase with increasing temperatures, while negative impacts decline. Also the wooded tundra shows a similar pattern. These changes dominate the global aggregation. The grassland/steppe ecosystem does not show pronounced differences but shows similar trends to those found in the tropical ecosystems. The largest neutral and negative changes occur in the boreal and temperate regions (Figure 3). Changes in the deciduous forests are all neutral, while boreal forests, cool conifer forests and temperate mixed forests the negative impacts decline with increasing temperatures.

Figure 3. percentage positive, neutral and negative changes for the different ecosystems based on the HADCM2 GCM.
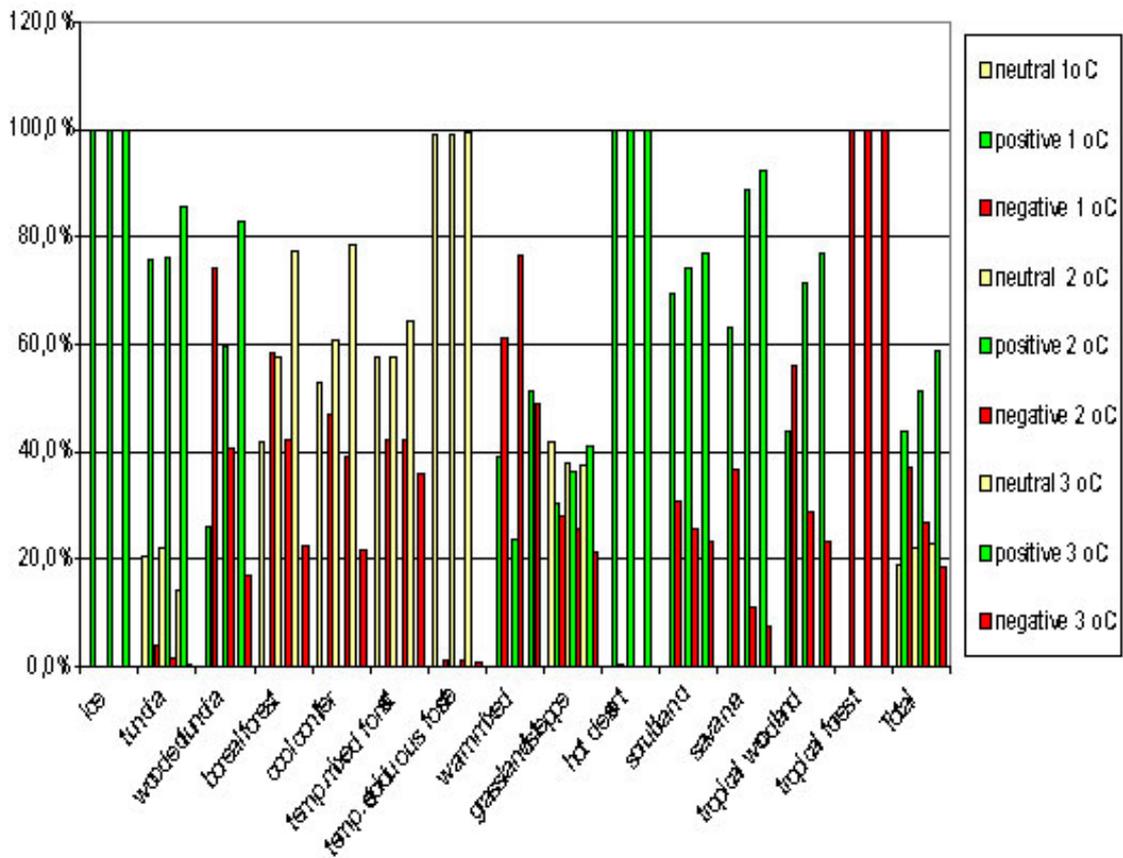
Here the "type of change" is defined on the basis of reducing limiting factors and enhancing the opportunities for human use. It looks strongly at the climatic potential and not at the actual dynamics. One can see an analogy with the discussion on carbon storage in the early nineties. Several studies showed that potentially more carbon could be stored in vegetation in a warmer climate (e.g. Smith *et al.*, 1992). The studies also emphasised the trend that had already started after the glacial maximum c. 18000 years ago, when climate warmed and peaked at the climatic optimum 6000 years ago. Unfortunately the current and projected climate change is much faster than the warming trend over the last 18000 years and there is ample evidence that ecosystems cannot keep pace with such rapid change and deteriorate, which results in rapid carbon loss (Neilson, 1993).

Also recent modelling studies illustrate such large uncertainty in materialising the potential benefits. The balance (NEP) between CO_2 uptake (NPP) and CO_2 release (soil respiration) is initially dominated by NPP and later by soil respiration because the latter increases exponentially with increasing temperatures, while photosynthesis has an optimum between 15 and 35 degrees depending on vegetation type. This is also clearly shown in an ecosystem model comparison (Cramer *et al.*, 1999), where several models were used to simulate the impact of a standardised climate change scenario. This scenario simulated a global mean temperature increase over 4 ^{o}C. Somewhere between 2 ^{o}C and 3 ^{o}C the analysis shows that soil respiration starts to dominate over photosynthesis, which leads to a rapid decline in NEP.

For determining the emerging benefits with climatic warming a similar rigorous analysis must be developed. Only when an ecosystems responds immediately by dispersing into new areas after a change in GMTI, such benefit is realised. This means that ecosystems should have unlimited migration capabilities (e.g. lichens), and that free habitats are also available. In real ecosystems, many species, such as trees, have long lifetimes and limited dispersal capacities. Davis (1989), for example, has established that maximum dispersal rates of common tree species are less than 100 km per century. Only when we assess the dispersal and establishment capabilities of species in the different ecosystems (i.e. the adaptation capacity) can we evaluate whether and when these potential benefits materialise.

IMAGE calculates if vegetation can adapt over a certain time period. Here we are only concerned with the areas that shift to another ecosystem and we want to know if that shift is possible. The algorithm evaluates the distance that has to be covered to reach the changed area. It checks dispersal rates, which are fast for grasses and slower for trees (van Minnen *et al.*, 2000). Here we have evaluated the changes over a period of a century. An increase in 1 ^{o}C GMTI in 2100 therefore is equivalent to a long-term 0.1 ^{o}C per decade as proposed as an upper limit by Vellinga and Swart (1991).

At a rate of warming of 0.1 ^{o}C per decade (i.e. 1°C GMTI in 2100), 50% of the impacted ecosystems are able to adapt within a century (Figure 4). This percentage increases only slowly when simulations continue beyond the first century, even when no additional increase in temperature are assumed. The adapted areas encompass immediate shifts along current ecosystem boundaries and vegetation that can easily adapt, such as grasslands. Further spread continues extremely slowly (up to 100 km per century). These findings are similar for other GCM patterns.

With increasing rates of change, the adaptation capacity rapidly declines. At a rate of warming of 0.3 ^{o}C per decade (i.e. 3°C GMTI in 2100), only 30% of the vegetation can adapt. With these larger increases in temperature, especially forest adaptation is limited to their ecosystem edges and boundaries. Further shifts lead to degraded ecosystems that will have consequences for carbon storage and all sectors, such as forestry and tourism, which are dependent on healthy ecosystems. These figures clearly indicate that the increasing potentially positive effects will not materialise during the first century. The transient dynamics matter and negative impacts will dominate. Unfilled habitats in ecosystems will probably be filled up rapidly by opportunistic 'generalists' species (Solomon and Leemans, 1990; Dukes and Mooney, 1999).

Figure 4. The impact and adaptation levels for different temperature changes based on the HADCM2 GCM and different SRES scenarios from the IMAGE CD-rom
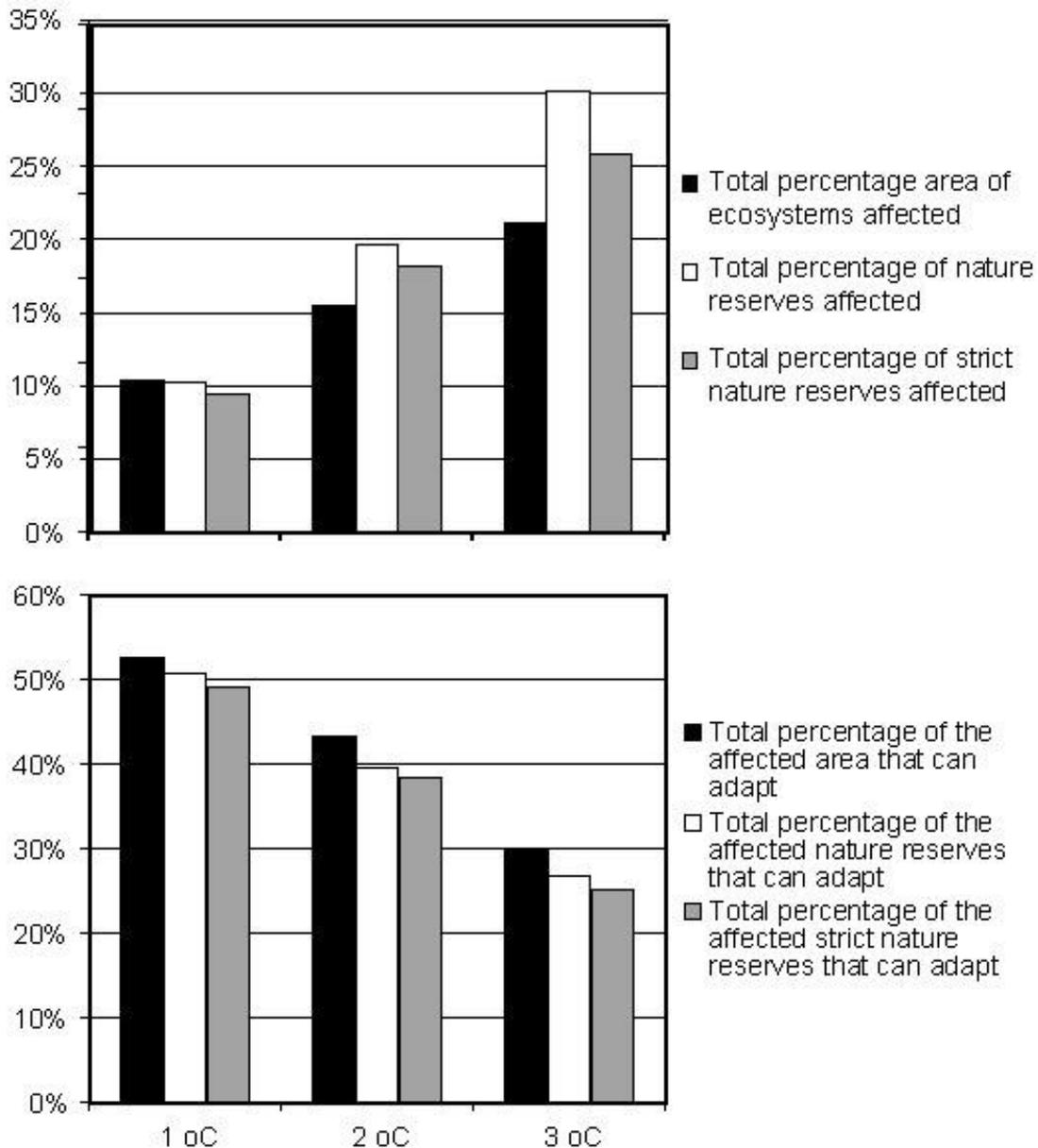
Source: IMAGE team, 2001

The extent of threatened nature reserves is another indicator that specifies climate impacts and one, which is also relevant for the Convention on Biodiversity. The database used includes data from all over the world and distinguishes between the multi-purpose and strict conservation reserves. Multi-purpose reserves are used for purposes other than conservation, while the latter represent the most valuable reserves for eco-system, habitat and species protection purposes.

Ecosystem change in nature reserves are similar to the patterns seen more generally (Figure 4). Impacts increase with increasing temperatures. Unfortunately impacts in all nature reserves increase faster

than in ordinary vegetation. With 3 ^{o}C GMTI, half of all nature reserves will not be capable of upholding the original conservation objectives. Even if we account for possible adaptation (Figure 4), nature reserves are less capable of adapting than ecosystems world-wide. This is caused by the uneven distribution of nature reserves. Many of them lie in sensitive and exposed biomes. Here we have still assumed that nature reserves are part of a continuous natural landscape. We have not considered the current situation of most reserves in fragmented, highly heterogeneous landscapes. This further reduces adaptation capabilities. These findings will surely jeopardise the WSSD objective to slow biodiversity decline in the coming decades.

5.   CONCLUSION REMARKS

The analysis clearly shows that even small climate change will have substantial consequences on temperature-limited ecosystems, such as tundras. Here the large-scale impacts will emerge first. All other ecosystems will, however, also be influenced. Here we have used a relatively simple but widely used vegetation model, embedded in a comprehensive integrated assessment model. Such an approach is adequate when regions have to be identified where changes will occur but very limited in determining when and how such changes will be triggered and evolve.

Straightforward assumptions on dispersal shows that forests ecosystems require the longest response times, while most other ecosystems respond more rapidly. The adaptive capacity of most forested ecosystems is thus low. The large changes that are projected in the boreal and temperature forests will probably not be realised during this century. There will be severe time lags in the response, which will lead to a sub-optimal functioning of these ecosystems or even increase their sensitivity to pests, fires and other disturbances, which are sources of additional stress. Also, the IPCC (Gitay *et al.*, 2002) stressed such increases in the vulnerability of ecosystems with increasing temperatures.

Mitigation strategies that rapidly reduce the projected increase in global mean temperature will limit the impacts of climate change on ecosystems. Every degree of avoided GMTI will substantially reduce impacts on ecosystems. However, even with a small GMTI, ecosystem impacts will be pronounced. These findings allow us to add an additional 'reason for concern' to the established by Smith *et al.*, 2001 in the IPCC Third Assessment Report. This added reason for concern shows the risks to regional and global ecosystems rapidly increasing with increasing temperatures (Figure 5). Risks for ecosystems increase rapidly above 1 to $2^{o}C$, mainly due to the lack of adaptation capacity in these systems. This finding is very similar to the first IPCC reason for concern (Smith *et al.*, 2001), which only focussed on local, unique and threatened ecosystems, such as alpine systems, coral reefs and mangroves.

Figure 5. Risk to regional and global ecosystems by global mean temperature change
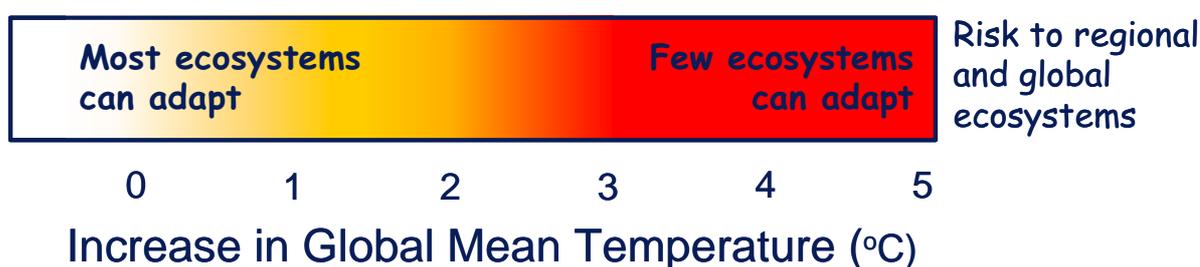
The rapid climate-change experiment that we are conducting with ecosystems will surely reduce biodiversity. These changes may simultaneously lead to significant economic damages related to ecosystem services. If we do not implement effective climate-mitigation policies soon, we jeopardise continuation of the current variation in ecosystems.

6. APPENDIX 1: SUMMARY STATISTICS

Summary Statistics for the shifts in ecosystems based on the HAD-CM2, GFDL LR15a, ECHAM4, CSIRO MK2 and CGCM1 GCMs, obtained from the IPCC data distribution centre

1 °C	Average	minimum	maximum	Average	minimum	maximum	Average	minimum	maximum	Average	minimum	maximum
Ice	-1,3%	-2,9%	-0,1%	98,0%	96,6%	98,9%	-2,0%	-3,4%	-1,1%	0,7%	0,5%	1,0%
tundra	4,2%	2,1%	5,3%	85,7%	84,4%	87,0%	-14,3%	-15,6%	-13,0%	18,5%	17,8%	19,0%
wooded tundra	-12,9%	-13,7%	-11,9%	53,2%	52,0%	53,9%	-46,8%	-48,0%	-46,1%	33,9%	32,9%	34,8%
boreal forest	-0,1%	-0,1%	0,0%	95,7%	95,7%	95,7%	-4,3%	-4,3%	-4,3%	4,2%	4,2%	4,2%
cool conifer	-8,7%	-8,7%	-8,6%	77,2%	77,2%	77,2%	-22,8%	-22,9%	-22,8%	14,2%	14,2%	14,2%
temp. mixed forest	16,5%	16,5%	16,5%	94,8%	94,8%	94,8%	-5,2%	-5,2%	-5,2%	21,7%	21,7%	21,7%
temp.deciduous forest	0,9%	0,9%	0,9%	88,3%	88,3%	88,3%	-11,7%	-11,7%	-11,7%	12,6%	12,6%	12,6%
warm mixed	2,8%	2,7%	3,0%	95,7%	95,6%	95,7%	-4,3%	-4,4%	-4,3%	7,1%	7,1%	7,3%
grassland/steppe	-4,9%	-5,2%	-4,6%	85,8%	85,4%	86,1%	-14,2%	-14,6%	-13,9%	9,3%	9,0%	9,7%
hot desert	-0,4%	-0,8%	0,3%	96,3%	96,1%	96,6%	-3,7%	-3,9%	-3,4%	3,3%	2,9%	3,7%
scrubland	-2,2%	-3,2%	-1,5%	78,8%	78,4%	79,3%	-21,2%	-21,6%	-20,7%	18,9%	18,0%	19,4%
savanna	-2,9%	-3,4%	-1,6%	86,9%	86,5%	87,6%	-13,1%	-13,5%	-12,4%	10,3%	10,0%	10,9%
tropical woodland	14,1%	13,1%	14,6%	91,8%	91,6%	91,9%	-8,2%	-8,4%	-8,1%	22,4%	21,3%	23,0%
tropical forest	-0,8%	-1,1%	-0,6%	95,3%	95,1%	95,5%	-4,7%	-4,9%	-4,5%	3,9%	3,8%	4,0%
Total	10,4%	10,2%	10,5%	89,6%	89,5%	89,8%	-10,4%	-10,5%	-10,2%	10,4%	10,2%	10,5%

2 °C	% change			% stable			% decrease			% increase		
	Average	minimum	maximum	Average	minimum	maximum	Average	minimum	maximum	Average	minimum	maximum
ice	-4,4%	-7,7%	-2,2%	95,3%	92,2%	97,0%	-4,7%	-7,8%	-3,0%	0,3%	0,1%	0,8%
tundra	-15,1%	-21,0%	-8,5%	71,9%	65,1%	79,5%	-28,1%	-34,9%	-20,5%	12,9%	12,0%	14,3%
wooded tundra	-2,6%	-5,1%	2,9%	34,3%	30,2%	42,2%	-65,7%	-69,8%	-57,8%	63,1%	52,7%	72,3%
boreal forest	1,1%	-0,3%	2,3%	89,9%	89,4%	90,5%	-10,1%	-10,6%	-9,5%	11,2%	10,0%	12,2%
cool conifer	9,9%	7,8%	12,9%	68,6%	67,8%	69,1%	-31,4%	-32,2%	-30,9%	41,3%	39,1%	43,8%
temp. mixed forest	25,9%	25,0%	27,2%	91,0%	90,4%	91,7%	-9,0%	-9,6%	-8,3%	34,9%	34,3%	35,6%
temp.deciduous forest	1,3%	-2,1%	2,5%	77,9%	75,7%	78,9%	-22,1%	-24,3%	-21,1%	23,4%	22,3%	24,3%
warm mixed	3,3%	2,6%	4,1%	90,0%	89,3%	90,4%	-10,0%	-10,7%	-9,6%	13,3%	12,5%	13,7%
grassland/steppe	-6,8%	-7,3%	-6,6%	79,9%	79,5%	80,6%	-20,1%	-20,5%	-19,4%	13,3%	12,8%	13,7%
hot desert	-2,1%	-3,0%	-0,3%	93,6%	93,1%	94,5%	-6,4%	-6,9%	-5,5%	4,3%	3,9%	5,2%
scrubland	-8,2%	-10,0%	-5,4%	74,0%	70,9%	75,6%	-26,0%	-29,1%	-24,4%	17,7%	15,0%	19,4%
savanna	-6,4%	-8,4%	-1,3%	81,6%	80,6%	84,1%	-18,4%	-19,4%	-15,9%	11,9%	10,3%	14,6%
tropical woodland	33,3%	30,8%	34,9%	89,9%	89,4%	90,5%	-10,1%	-10,6%	-9,5%	43,4%	40,7%	45,4%
tropical forest	-0,9%	-3,0%	0,9%	91,7%	89,8%	93,0%	-8,3%	-10,2%	-7,0%	7,4%	7,2%	7,8%
Total	15,9%	15,5%	16,3%	84,1%	83,7%	84,5%	-15,9%	-16,3%	-15,5%	15,9%	15,5%	16,3%

3 °C	% change				% stable				% decrease				% increase		
	Average	min	max		Average	minimum	maximum		Average	minimum	maximum		Average	minimum	maximum
ice	-6,7%	-9,8%	-4,7%		93,2%	90,1%	95,0%		-6,8%	-9,9%	-5,0%		0,1%	0,0%	0,3%
tundra	-42,7%	-50,8%	-32,9%		51,5%	42,4%	61,6%		-48,5%	-57,6%	-38,4%		5,8%	5,3%	6,8%
wooded tundra	9,4%	3,3%	18,3%		27,1%	23,4%	32,2%		-72,9%	-76,6%	-67,8%		82,3%	71,2%	94,4%
boreal forest	5,1%	3,3%	6,9%		88,3%	87,8%	88,9%		-11,7%	-12,2%	-11,1%		16,8%	15,4%	18,2%
cool conifer	9,8%	-3,3%	18,0%		50,1%	39,7%	55,7%		-49,9%	-60,3%	-44,3%		59,7%	56,2%	63,0%
temp. mixed forest	37,6%	33,7%	43,0%		86,9%	85,7%	89,5%		-13,1%	-14,3%	-10,5%		50,7%	47,2%	53,6%
temp.deciduous forest	1,8%	-4,1%	5,0%		72,0%	68,5%	74,4%		-28,0%	-31,5%	-25,6%		29,8%	27,5%	30,9%
warm mixed	4,2%	1,7%	6,9%		83,9%	82,8%	84,2%		-16,1%	-17,2%	-15,8%		20,3%	18,4%	23,0%
grassland/steppe	-8,8%	-9,5%	-7,2%		72,4%	71,0%	74,8%		-27,6%	-29,0%	-25,2%		18,8%	17,9%	19,7%
hot desert	-6,1%	-8,4%	-3,6%		88,8%	87,3%	90,5%		-11,2%	-12,7%	-9,5%		5,1%	4,3%	5,9%
scrubland	-9,9%	-14,1%	-3,4%		64,1%	58,4%	68,3%		-35,9%	-41,6%	-31,7%		26,0%	19,4%	30,5%
savanna	-9,6%	-12,0%	-5,6%		73,4%	73,2%	74,2%		-26,6%	-26,8%	-25,8%		17,0%	13,8%	21,2%
tropical woodland	54,7%	49,8%	61,3%		91,4%	90,4%	92,1%		-8,6%	-9,6%	-7,9%		63,4%	58,2%	69,6%
tropical forest	1,0%	-2,7%	5,2%		91,4%	87,7%	95,0%		-8,6%	-12,3%	-5,0%		9,6%	8,8%	10,2%
Total	21,9%	21,1%	23,5%		78,1%	76,5%	78,9%		-21,9%	-23,5%	-21,1%		21,9%	21,1%	23,5%

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