

Another reason for concern: regional and global impacts on ecosystems for different levels of climate change

Rik Leemans^{a,*}, Bas Eickhout^b

^a *Environmental Systems Analysis, Wageningen University, P.O. Box 47, 6700 DD Wageningen, The Netherlands*

^b *Office of Environmental Assessment, P.O. Box 1, 3720 BA Bilthoven, The Netherlands*

Abstract

This study assesses the impacts of climate change on species, ecosystems and landscapes over a range of increasing global mean temperatures and the corresponding temperature and precipitation patterns. Results from IMAGE, a so-called integrated assessment model, are used to link different ecological impacts to different levels of climate change. The analysis shows that, although there are large regional differences, even small increases in global mean temperatures will considerably impact many species, ecosystems and landscapes. Between 1°C and 2°C increases in global mean temperatures most species, ecosystems and landscapes will be impacted and adaptive capacity will become limited. With the already ongoing high rate of climate change, the decline in biodiversity will therefore accelerate and simultaneously many ecosystem services will become less abundant.

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1. Introduction

Climate and weather directly control the distribution, productivity and many other aspects of species, ecosystems and landscapes. Each climate zone is characterised by its typical ecosystems. The early explorers already knew this. They described climate on the basis of ecosystem observations and vice versa. This climatic control is therefore used to develop climate-classification models that describe large-scale terrestrial ecosystem¹ patterns (e.g. Cramer and Leemans, 1993) and marine ecosystems (Pauly and Christensen, 1995).

Large-scale ecosystem patterns will thus be influenced by climate change. Historical changes have been reconstructed on basis of pollen deposits, tree rings and other means (e.g. Huntley and Webb, 1988). Such studies have shown that in the past, on a millennium time scale ecosystems have been in close equilibrium with climate. 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. Additional heterogeneity in landscapes results from time lags due to ecological succession after disturbances. Furthermore, over the last millennia humans have managed species, ecosystems and landscapes to obtain specific goods and services. Humans currently dominate many ecosystems.

Climate change will influence many species distributions and ecosystem processes. Emanuel et al. (1985), who used the Holdridge 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-CO₂ climate. Their pioneering result compares well with recent studies, which have added more spatial detail, used dynamic models, more realistic species and ecosystem responses, and more comprehensive climate scenarios.

Smith et al. (2001) synthesised all possible information on climate-change impacts to evaluate which impact level would constitute a dangerous climate change. They used global mean temperature increase (GMTI) in 2100, which is a widely accepted climate-change indicator, and determined related risk levels

*Corresponding author. Tel.: +31-317-484-919; fax: +31-317-484-839.

E-mail addresses: rik.leemans@wur.nl (R. Leemans), bas.eickhout@rivm.nl (B. Eickhout).

¹We use the term 'ecosystems' in a very broad sense here as large-scale vegetation patterns or biomes.

(low, medium and high) for 5 different ‘Reasons for concern’ characterised by specific entities (e.g. unique and rare species, extreme events, regional distribution, aggregated impacts and large-scale singularities). Unfortunately, most impact assessments were based on scenarios, which almost always focussed on ‘doubled- CO_2 conditions’ or beyond with, consequently, a relatively high GMTI. Smith et al. (2001) used observed impacts to derive risk levels at lower GMTI. Initially, this was found to be controversial (Parmesan and Yohe, 2003) but since several additional long-term observations have been analysed (e.g. Thompson et al., 2002; Root et al., 2003; van Herk et al., 2002), which all point to significant climate-change impacts throughout the world. There is now ample evidence that species and ecosystems are sensitive even to small changes in GMTI.

Here, we will focus on comprehensively estimating impact levels of climate change on terrestrial ecosystems during this century. 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. Shifts in terrestrial ecosystems will be further quantified in order to also highlight regional aspects. The ecosystem impacts will be determined by using the IMAGE model (Alcamo et al., 1998) and its implementation of the IPCC-SRES scenarios (IMAGE team, 2001a,b), which include several climate-change patterns obtained from advanced climate models (i.e. General Circulation Models: GCMs) and high, medium and low climate sensitivities. This helps to address some of the major uncertainties in regional climate-change patterns.

By using a model like IMAGE, we can comprehensively relate regional impacts to GMTI. Although GMTI is defined for a 100-year period, this indicator remains difficult to link to dynamic aspects of ecosystem responses. If a 2°C increase occurs over 1000 years (i.e. 0.02°C per decade), most affected ecosystems are likely to adapt, while when such increase happens over 50 years (i.e. 0.4°C GMTI per decade) many ecosystems will rapidly deteriorate. The rate of change (or the period over which such change lasts) is important for defining the absolute impact. To analyse some of the consequences of different rates of change, we further assess how ecosystems, especially nature reserves, can adapt to different GMTI in 2100.

These large-scale impacts on species, landscapes, ecosystems and many of 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 specific

ecosystem services (e.g. crops and timber) can be estimated in dollars (e.g. Balmford et al., 2002), we believe that the actual damages or benefits of changes in species, ecosystems and landscapes are not satisfactorily characterised in monetary terms. Further, many important aspects of ecosystems are trivialised or marginalized when converted to monetary terms through selection of 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 start by presenting only a short summary of the IMAGE model because the model is fully documented elsewhere (e.g. Alcamo et al., 1998). Then we discuss which output indicators we derived from the IMAGE results to define the different impact levels. Earlier, changes in ecosystems were presented as always detrimental. By looking at regional changes, we have tried to distinguish between positive, neutral and negative changes. Finally, we evaluate the impacts on nature reserves, which are areas that are legally protected to maintain original valuable species and ecosystems. All these different aspects of ecosystems provide a comprehensive global and regional assessment of climate-change risks to ecosystems, which we summarise as a sixth ‘Reason for concern’.

2. Methodology

Different ecosystem models are currently found in integrated assessment models (IAMs) that simulate the causal chain of emissions, concentration, climate change, impacts and responses. IAMs are used to generate comprehensive scenarios of human activities (energy use, land use and industrial activities) and the consequential emissions. The most widely used set of scenarios in climate-change impact assessments is now the set of IPCC-SRES scenarios (Nakicenovic et al., 2000). Here we have used the IMAGE model and its 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 have been developed to simulate the consequences of changes in atmospheric CO_2 concentrations and climate on natural ecosystem 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° 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 GMTI with the pattern of temperature and precipitation change from a specific GCM and normalised by its climate sensitivity. This results in a change in regional pattern of temperature and precipitation, which is combined with current climate to obtain future climate for each IMAGE grid cell. We have used several GCMs to analyse the uncertainty stemming from different climate-change patterns (IMAGE team, 2001b).

The terrestrial vegetation model computes the potential distribution of natural ecosystems. 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 ecosystem patterns. As temperature and moisture patterns change, computed ecosystem patterns shift. Such a shift, however, takes time and would not occur immediately due to the lack of better-adapted plant types in the surroundings. Although BIOME calculates an instantaneous *equilibrium* response to climate change, IMAGE explicitly simulates lags in ecosystem responses (van Minnen et al., 2000).

The Terrestrial Carbon model (Alcamo et al., 1998) 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 turnover time after which most of the C becomes part of the organic C pools in the soil. 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 CO₂ concentrations, climate and other factors on NPP and respiration rates, and the ecosystem 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 in IMAGE strongly depends on the interactions of all these factors.

IMAGE automatically calculates the effects of land-cover transitions, and changes in atmospheric CO₂ concentrations and climate on NPP and NEP. When natural ecosystems become agricultural land the C stored in the original vegetation is released. When agricultural land is abandoned or becomes unsuitable under climate change, the natural ecosystems, which are always kept in the background of an agricultural land cover type, emerges again. Also after timber extraction C storage in ecosystems is adjusted. Ecosystems shifts—from one natural ecosystem type towards another—due to climate and CO₂ concentration change is simulated by a lagged response using a linear interpolation, which parameterises different ecosystems transitions between original and new ecosystem types (van Minnen et al., 2000). The processes involved are strongly influenced by the rate of climate change, the total area of ecosystems at risk and the possibility for natural land-cover types to adapt to new conditions.

We have used the IPCC-SRES scenarios as implemented by the IMAGE team (2001a,b). These scenarios are based on different narratives (Nakicenovic et al., 2000) that depict different plausible future worlds. It goes beyond the scope of this paper to describe these scenarios in detail. All the data is available in CD-rom form (IMAGE team, 2001a,b).

We have used several IPCC-SRES scenarios to be able to use different magnitudes and rates of GMTIs. For illustration purposes we limited ourselves to a range of GMTIs in 2100 of 1°C, 2°C and 3°C. This corresponds to 0.1°C, 0.2°C and 0.3°C per decade, respectively.

2.1. Climate and impact indicators

The indicators that we used for this paper are all relatively straightforward to calculate. First, we relate the impact levels to GMTI. 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 to larger impacts than just temperature change in many regions. The highest temperature increases are found in the high-latitude regions, where ecosystems are mostly temperature limited. The largest impacts of changes in moisture availability are in arid and semi-arid regions.

Another climate-related indicator is the rate of global mean temperature change. This indicator is helpful to estimate adaptive capacity of ecosystems. Among the first to use this indicator are Vellinga and Swart (1991). They arbitrarily defined a threshold of 0.1°C per decade (i.e. 1°C per century) under which most ecosystems could adapt. Swart et al. (1998) have used results from the ecosystems migration and adaptation routine of IMAGE to show that ecosystem types like grass and desert can adapt quickly to climate change. Forest

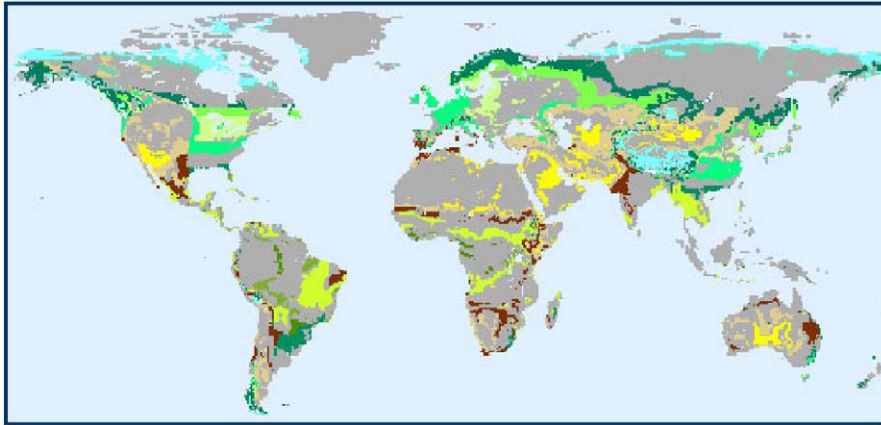


Fig. 1. Shifts in ecosystems for a global mean temperature increase of 3°C and the HADCM-GCM climate change patterns. The colours depict different ecosystems that are impacted (forests are green, grasslands are brown and deserts are yellow).

ecosystems, however, adapt with more difficulty to climate change. Swart et al. (1998) estimated that only at a rate of less than 0.05°C per decade could most forested ecosystems adapt to the climate changes simulated for the 21st century. In this study, we estimate the rate of change on the basis of the global mean temperature in 2100, e.g. a 1°C temperature increase in 2100 coincides with an average change of 0.1°C per decade, a 2°C increase averages 0.2°C change per decade and so on. Unfortunately, the IMAGE scenarios did not provide lower rates of changes because climate-policy scenarios were not available.

The major impact indicator that we use is shifts in ecosystems. Climate warming leads to a polewards or upwards shift in many ecosystems. We have calculated for each ecosystem the current and future extent or area (in km²). These shifts are, however, more complex than just changes in net extent. In some regions, an ecosystem's extent is reduced, while in other regions it actually expands. We therefore use four different indicators to completely describe the shifts. First is the net change in extent. This change results from the net effect of reductions and expansions worldwide and can be positive (an overall increase in extent) or negative (a overall decrease in extent). The remaining three indicators breakdown the individual components of net changes as described above. Thus, the second indicator shows stable area, which is the part of an ecosystem's area that does not change. The third indicator is the reduction in area, which only quantifies the area where disappearance of ecosystem area occurs. The fourth and last indicator is the increase or expansion of area, which indicates the future area into which species from the ecosystem disperse. The original area of an ecosystem is equal to the stable area plus the reduction in area, while the future area (with climate change) is the stable area plus the increase in area. The data is both available in absolute terms (change in area) and relative terms

(percentage change relative to the area in 1990) and each set of changes is calculated for 1°C, 2°C and 3°C, respectively. The magnitude of changes and regional patterns are presented in Fig. 1 for 3°C.

Not all changes are alike. Some of the changes are positive. Positive shifts are generally characterised by shifts from deserts to grasslands or from grasslands to forests. Here NEP of an ecosystem increases and there are more opportunities for managing ecosystem services. Neutral changes are those where ecosystems are replaced by ecosystems with similar productivity characteristics but composed of different species. 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. Table 1 defines which changes are positive, neutral and negative.

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. In human-dominated landscapes there is little room for large patches of natural ecosystems, where typical successional and disturbance patterns can develop. In these landscapes, nature reserves are created to prevent unique species and ecosystems from extinction. 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 ecosystem 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 (see 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.

Table 1
Definition of positive (+), neutral (O) and negative (–) shifts in ecosystems compared to 1990 ecosystems

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

3. Results

The shifts in ecosystems show that even with a small climate change the impacts on terrestrial ecosystems are pronounced (see Fig. 2). A 1°C warming alters more than 10% of all ecosystems (global average is 10.4%; range for the different GCMs is 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 ecosystems (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. Similar global magnitudes arise for across the GCMs (for details see Leemans and Eickhout, 2003).

Ecosystem impacts increase with increasing temperatures. At 2°C and 3°C only 84% and 78% of all terrestrial ecosystems, respectively, are stable. 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 CO₂ concentrations that are included in IMAGE.

Current tropical forests and woodlands are relatively stable across the 1–3°C GMTI range (95.3 to 91.4%, respectively, of its current area remains stable). Most of 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 ecosystems model, however, is very drought sensitive and linked to just the one GCM that strongly 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 and disturbances. These aspects seem real but are not simulated by IMAGE.

The temperate and boreal forests show larger shifts. Only 50.1–86.9% of these ecosystems are stable with a

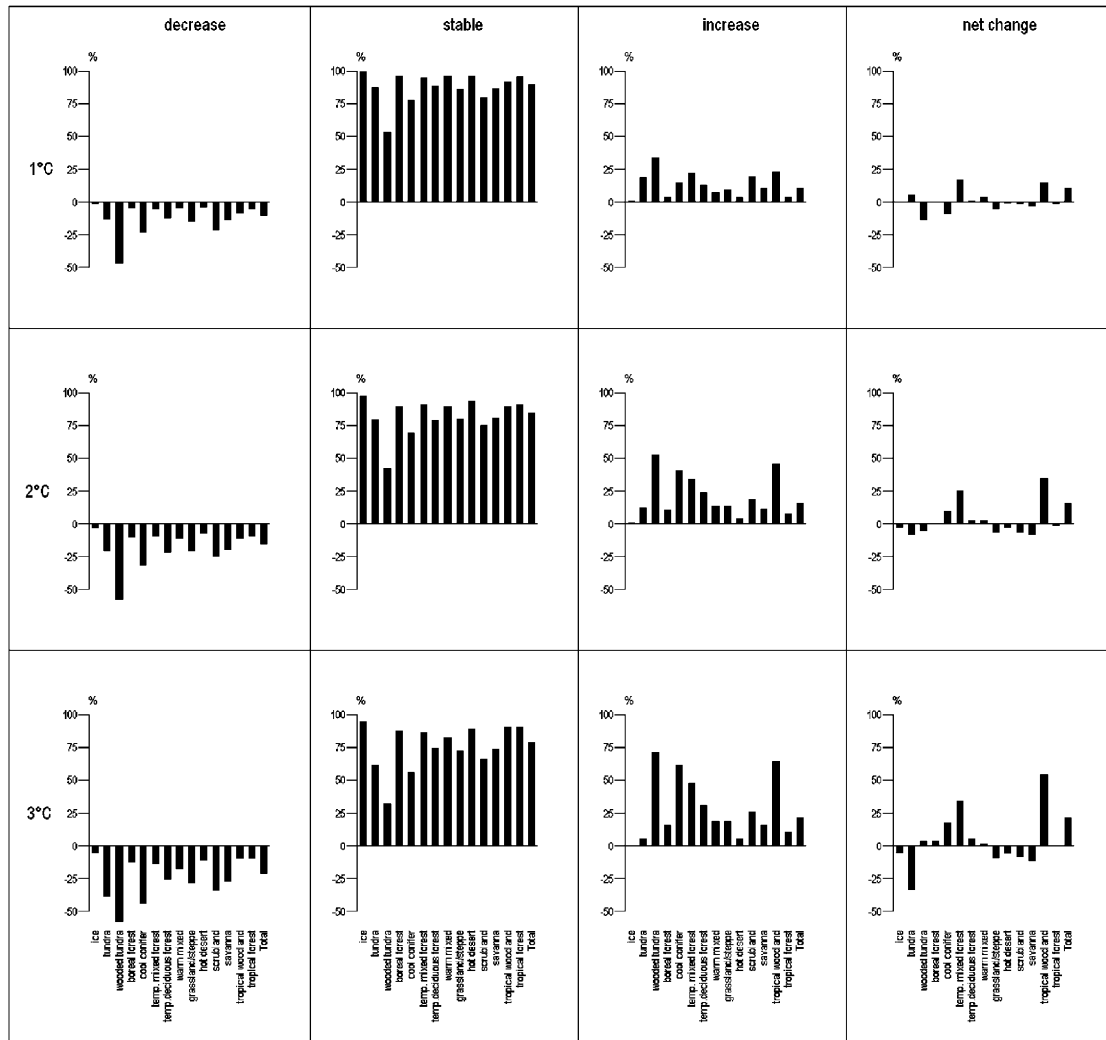


Fig. 2. Different changes in area of specific ecosystems for a global mean temperature increase of 1°C (top), 2°C (middle) and 3°C (bottom). Notes: From left to right is presented the decrease in area, the area that is stable (i.e. no impact), the increase in area, and the net change in area. The patterns in this figure are based on the climate-change patterns of the HADCM-GCM.

3°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 Fig. 2). Worldwide however, there is an increase in temperate forests.

The wooded tundra is strongly reduced in area, because boreal forests replace it. On average only 27% (range 23–32%) of the original ecosystems remain in place with a 3°C GMTI. Even with a modest 1°C GMTI only 53% (range 52–54%) remain stable. Here is the largest risk for accelerated species extinctions, which will also impact other regions because several migratory bird species use this ecosystem as 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.

Globally 21.9% (range 21.1–23.5%) of all ecosystems show a net change in extent with a temperature increase of 3°C. The magnitude of this change is reduced but does not disappear at 2°C and 1°C GMTI, where the average changes are 15.9% (range 15.5–16.3%) for 2°C and 10.4% (range 10.2–10.5%) for 1°C GMTI. Although the ranges are large (i.e. 7.0–74% for 3°C, for 5.0–66% for 2°C and 2–47% for 1°C), all ecosystems show smaller impacts at lower increases in GMTI. The magnitude of change in net extent increases rapidly initially and then declines with GMTIs. The range expansions in individual ecosystems are of similar magnitude to the figures for declines in ecosystems. This shows that a global aggregation can easily underestimate the actual impacts on ecosystems by not necessarily highlighting disappearance when it occurs.

Analysis of the type of change associated with GMTI by ecosystem category (see Table 1) provides additional

insights. Globally (see Fig. 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 ecosystem driven changes in the ice, tundra, and hot desert ecosystem categories are by definition positive, while changes in tropical forests are by definition negative. In 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 (see Fig. 3). Changes in the deciduous forests are all neutral, while in boreal forests, cool conifer forests and temperate mixed forests the negative impacts decline with increasing temperatures.

Here the “type of change” is defined on the basis of reducing limiting factors and enhancing the

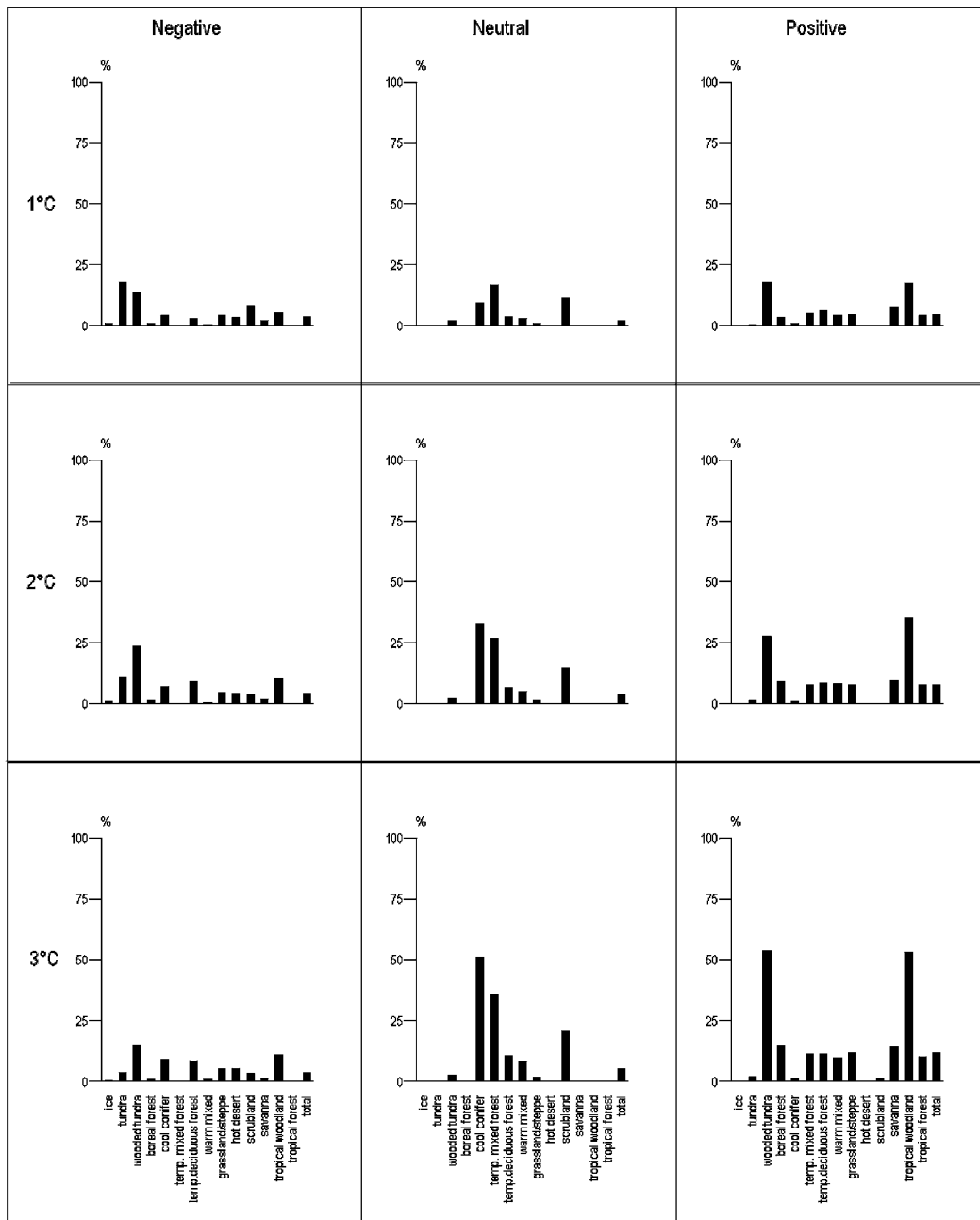


Fig. 3. Type of impact for specific ecosystems for a global mean temperature increase of 1°C (top), 2°C (middle) and 3°C (bottom). Notes: From left to right is presented the negative, neutral and positive impacts. The patterns in this figure are based on the climate-change patterns of the HADCM-GCM.

opportunities for human use. It looks 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 ecosystems 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. 18,000 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 18,000 years and there is ample evidence that ecosystems cannot keep pace with such rapid change and deteriorate, which results in rapid carbon loss.

Recent modelling studies illustrate large uncertainty in estimating the potential benefits of limiting global warming. The balance (NEP) between CO₂ uptake (NPP) and CO₂ release (soil respiration) is initially dominated by NPP and later by soil respiration. This is because the latter increases exponentially with increasing temperatures, while photosynthesis has an optimum between 15°C and 35°C depending on ecosystem type. These interactions are clearly shown in an inter-comparison of ecosystem models and their results (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 of over 4°C. Somewhere between 2°C and 3°C the analysis shows that soil respiration starts to dominate over photosynthesis, which leads to a rapid decline in NEP.

Determining the emerging benefits of climatic warming requires a similar but much more rigorous analysis. Only when an ecosystem responds immediately by dispersing into new areas after a change in GMTI are such benefits realised. The IMAGE simulations show that this is only the case for rapidly adapting ecosystems such as deserts and grasslands (at 1°C, 2°C or 3°C GMTI in 2100: 88%, 84%, 81% of the respective ecosystem areas adapt) but not for forest ecosystems (at 1°C, 2°C or 3°C GMTI in 2100: 36%, 25%, 17% of the respective ecosystem areas adapt). The adaptive capacity of forests rapidly declines at increasing GMTIs. 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 adaptive capacity) can we evaluate whether and when these potential benefits materialise.

IMAGE calculates whether ecosystems 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°C GMTI in 2100 therefore is equivalent to a long-term 0.1°C per decade as proposed as an upper limit by Vellinga and Swart (1991).

At a rate of warming of 0.1°C per decade (i.e. 1°C GMTI in 2100), 50% of all impacted ecosystems are able to adapt within a century (see Fig. 4) but only 36% of all impacted forests. Even when no additional increase in temperature is assumed, this percentage of ecosystems able to adapt increases only slowly when simulations continue beyond 2100. The adapted areas encompass immediate shifts along current ecosystem boundaries and ecosystems that can easily adapt, such as grasslands. Further spread continues at an extremely slow pace (up to 100 km per century). These findings are similar for other GCM patterns.

With increasing rates of change, the adaptive capacity of ecosystems rapidly declines. At a rate of warming of 0.3°C per decade (i.e. 3°C GMTI in 2100), only 30% of all impacted ecosystems can adapt, and only 17% of all impacted forests. 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 economic sectors that depend on related goods and services and “healthy” ecosystems, such as forestry and tourism. These figures clearly indicate that potentially positive effects will not increase during this 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).

The area 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-driven changes in nature reserves are similar to the patterns seen more generally. Impacts increase with increasing temperatures. Unfortunately impacts in all nature reserves increase faster than in ordinary ecosystems. With 3°C GMTI, half of all nature reserves will not be capable of meeting the original conservation objectives. Even if we account for possible

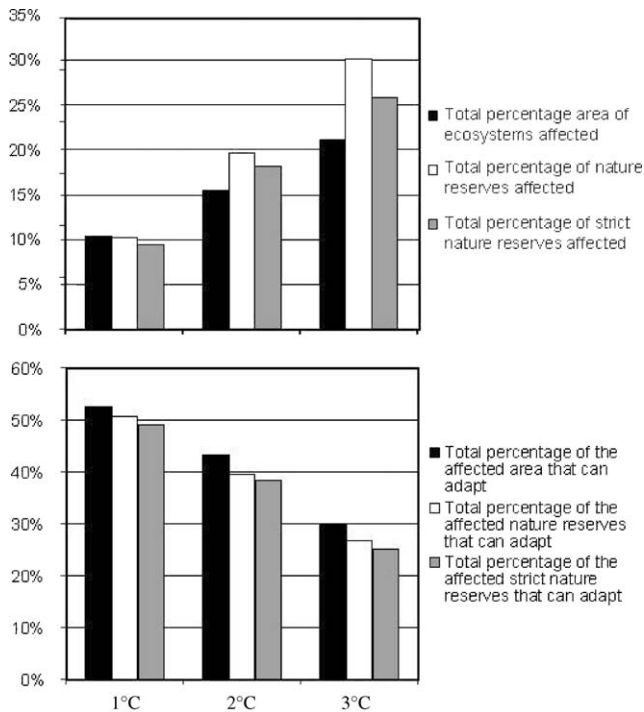


Fig. 4. Impact (top) and adaptation levels *(bottom) of all ecosystems, all nature reserves and strict nature reserves. Notes: For a global mean temperature increase of 1°C, 2°C and 3°C based on the HADCM2 GCM.

adaptation (see Fig. 4), nature reserves are less capable of adapting than ecosystems worldwide. 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 adaptative capacity of ecosystems. These findings will surely jeopardise the achievement of the WSSD objective to slow biodiversity decline in the coming decades.

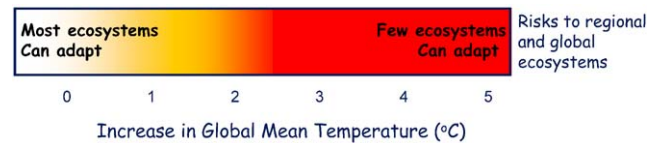
4. Concluding remarks

We have used a relatively simple but widely used ecosystem model, embedded in a comprehensive integrated assessment model. Such an approach is adequate to identify regions where changes will occur but is very limited for determining when and how such changes will be triggered and evolve. The analysis clearly shows that even small climate changes will have substantial consequences on temperature-limited ecosystems, such as tundra. Our findings suggest that the large-scale impacts will occur first. All other ecosystems will, however, also be influenced but there are large regional differences depending on the original species, ecosystem

and landscape, their sensitivity and exposure to regional changes in temperature and precipitation patterns.

Not all impacts are negative. For example, tundra that is replaced by forests could potentially store more carbon and provide additional ecosystem services (e.g. wood). However, the decline of stressed species and ecosystems is generally a fast process (years to decades), often triggered by disturbances, while adaptation through migration and regrowth is a slow process (decades to centuries to millennia).

Straightforward assumptions on dispersal show 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 temperate 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 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 those established by Smith et al. (2001) in the IPCC Third Assessment Report: ‘Risk to regional and global ecosystems’. This additional concern shows the risks to regional and global ecosystems rapidly increasing with increasing temperatures. Even with small changes in GMTI risks cannot be neglected but they increase rapidly above 1°C to 2°C GMTI, mainly due to the lack of adaptation capacity in these systems. This finding is complementary to the first IPCC ‘Reason for concern’, which only focussed on local, unique and threatened ecosystems, such as alpine systems, coral reefs and mangroves.

This study is the first model-based assessment where both smaller and larger changes in climate are considered. The analysis indicates that even small magnitudes of climate change will impact species, ecosystems and landscapes considerably. With the already ongoing high rate of climate change (i.e. larger than 0.2°C per decade), a decline in biodiversity and many ecosystem services will accelerate soon. Both this model analysis

and already observed impacts indicate this. If we do not implement effective climate mitigation and impact adaptation strategies soon, the current variation in species, ecosystems and landscapes will be lost.

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