ORIGINAL ARTICLE

Towards a general relationship between climate change and biodiversity: an example for plant species in Europe

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Abstract Climate change is one of the main factors that will affect biodiversity in the future and may even cause species extinctions. We suggest a methodology to derive a general relationship between biodiversity change and global warming. In conjunction with other pressure relationships, our relationship can help to assess the combined effect of different pressures to overall biodiversity change and indicate areas that are most at risk. We use a combination of an integrated environmental model (IMAGE) and climate envelope models for European plant species for several climate change scenarios to estimate changes in mean stable area of species and species turnover. We show that if global temperature increases, then both species turnover will increase, and mean stable area of species will decrease in all biomes. The most dramatic changes will occur in Northern Europe, where more than 35% of the species composition in 2100 will be new for that region, and in Southern Europe, where up to 25% of the species now present will have disappeared under the climatic circumstances forecasted for 2100. In Mediterranean scrubland and natural grassland/steppe systems, arctic and tundra systems species turnover is high, indicating major changes in species composition in these ecosystems. The mean stable area of species decreases mostly in Mediterranean scrubland, grassland/steppe systems and warm mixed forests.

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Introduction

Anthropogenic climate change already impacts species and ecosystems to a large extent, especially in vulnerable systems like polar systems and mountain areas (Walther et al. 2002; Parmesan and Yohe 2003; Root et al. 2003; Gregory et al. 2009). In north-western Europe, thermophilic (heat-demanding) plant species have become significantly more frequent compared to 30 years ago—in the Netherlands, by around 60% (EEA 2004). Many European birds have shifted their main about 20 km northward from about 1970 to 1990, and butterflies shifted about 150 km in a similar period (Parmesan et al. 1999; Thomas and Lennon 1999). In the Netherlands, several lichen species, having their main distribution in tropical and subtropical areas, increased during the last 30 years, while boreal species decreased (Van Herk et al. 2002). More and more studies demonstrate shifts in species distribution, associated with decreases in local species population (Walther et al. 2005; Both et al. 2006; Loebl et al. 2006). Most studies demonstrate also other factors of change (such as land use), but a significant part of the variability can only be attributed to climate change. A global overview of such ecological responses to climate is provided by Parmesan (2006).

Observed effects on species coincide with a global mean temperature increase (GMTI) of 0.6°C in the twentieth century (IPCC 2001), indicating causality. GMTI is expected to continue with levels between 1 and 6°C in the twenty-first century (IPCC 2001). The increased impact of climate change on ecosystems is one of the most important concerns for the twenty-first century (Smith et al. 2009).

The role of climate change as one of the major drivers of global and regional biodiversity loss has been recognized for some time (Sala et al. 2000; Petit et al. 2001; Potting and Bakkes 2004; Millennium Ecosystem Assessment 2005). These global and regional studies used expert judgments or models at the biome level to assess the relative contribution of climate change, land use change, nitrogen deposition and several other drivers of biodiversity change. At the level of individual species, impacts of climate change have also been documented by many authors (e.g., Huntley et al. 1995; Sykes et al. 1996; Peterson et al. 2001, 2002; Bakkenes et al. 2002; Beaumont and Hughes 2002; Erasmus et al. 2002; Araujo et al. 2006; Broennimann et al. 2006; Thuiller et al. 2006). These studies mainly used so-called climate envelope models of individual species to estimate changing species abundance and to derive overall biodiversity change from this. These models provide insights into likely future impacts of climate change since they allow for the analysis of species distribution shifts, shifts of functional types and extinction of species (Thomas et al. 2004; Thuiller et al. 2004; Bakkenes et al. 2006). Climate envelope models, however, are data dependent. They are only available for a few regions and species groups and therefore are of limited use in global assessments that focus on the combined effects and relative contribution to biodiversity changes.

In this study, we propose a methodology to derive general relationships between climate change and biodiversity loss from climate envelope models (CEM), which can be used in assessments including climate change effect in conjunction with other environmental pressures. These relationships describe relative changes compared to a standard situation (Sala et al. 2000; Petit et al. 2001; Potting and Bakkes 2004). The approach focuses on impacts on areas, because this allows to aggregate different impacts on a specific area.

We applied this methodology for European biomes using CEMs for plant species (Bakkenes et al. 2002). We use multiple climate change scenarios with the CEMs in order to derive a general relationship between the global mean temperature increase (GMTI) and the average relative change in species distributions. This approach provides conclusions on quality of natural areas in a future forecasted climate.

Methods

Relative measure of change

As indicators for the relationship between climate change and biodiversity, we use the mean stable area for all species and the species turnover for an area, thereby combining species loss and species gain. These measures are used in climate impact studies based on CEMs (Bakkenes et al. 2002; Broennimann et al. 2006; Thuiller et al. 2006). We applied CEMs of European plant species to different climate change scenarios until 2100. We calculated mean stable area and species turnover for each biome and each scenario and finally derived linear regression equations relating mean stable area and GMTI.

The species stable area and the species turnover indicators depend on the level of climate change and on the vulnerability of an ecosystem. These measures can be regarded as indicators for biodiversity in the sense of the CBD indicator "trends in abundance and distribution of selected species" appearing on the list agreed upon in the 7th Conference of Parties in Kuala Lumpur (UNEP 2004).

Stable area of a species is defined as the area in which the species remains after climate change. A stable area close to 100% reflects the original distribution, whereas a value of 0% means that the species is projected to be completely displaced or 'locally' extinct. The mean stable area is calculated by taking the average of the stable areas of all species present within each biome. In this study, we use only those species that in 1995 occupied more than approximately 2,500 km^2.

Species turnover for a biome is defined as $100 \times (G + L)/(N + G)$, where G is number of species entering the area currently occupied by that biome, assuming complete dispersal, L is the number of species disappearing from that area, and N is the number of species now present in this biome. A species turnover of 0% means no change, whereas a turnover of 100% means a complete shift of species composition of an ecosystem.

We estimate species distributions on a grid of approximately 2,500 km^2 mesh size for the current (1995) and forecasted situation (2100) for each climate scenario. For each grid cell, the proportion of remaining species and the proportion of new species, assuming complete and instantaneous dispersal, are calculated in order to map plant biodiversity change (Bakkenes et al. 2006). Species stable area and species turnover were derived from these maps and summarized for each (European) current biome. We use the biome classification as a geographical division so that shifts of the biomes were not taken into account.

Climate envelope models

The climate envelope models of European vascular plant species were derived from the EUROMOVE model (Bakkenes et al. 2002). We selected the 856 models that have a fair to good correspondence (kappa statistic > 0.4) with the underlying data (Bakkenes et al. 2006). The climate envelopes were estimated using logistic regression analysis by relating six climatic variables provided by the

IMAGE model (Alcamo 1994; Bouwman et al. 2006) and species data from the Atlas Florae Europaeae (AFE) (Jalas and Suominen 1989). The model uses the following climatic variables: (1) temperature of the coldest month; (2) effective temperature sum above 5°C; (3) alpha soil moisture index; (4) annual precipitation; (5) length of growing season and (6) mean growing season temperature above 5°C.

Climate scenarios

We used scenarios comprising a baseline scenario leading to high climatic impacts and two alternative GHG emission profiles aimed at stabilization of greenhouse gas concentrations and therefore lower climatic impacts (Bakkenes et al. 2006). The baseline scenario covers different characteristics of the IPCC Special Report on Emission Scenarios (SRES, Nakicenovic and Swart 2000) and a stabilizing global population of 9 billion by 2050 (Van Vuuren et al. 2003). The baseline scenario—depicting possible greenhouse gas (GHG) emission trends in the absence of climate policies—leads to a global mean temperature increase (GMTI) of more than 3°C over pre-industrial levels by 2100. The two alternative global emission profiles for stabilizing GHG concentrations at 550 and 650 ppmv CO_2 equivalent result in a GMTI of 2°C and 2.3°C by 2100, respectively (Eickhout et al. 2003). The global mean temperature increase, as calculated by the IMAGE model, is linked to climate patterns generated by a general circulation model (HadCM2, Mitchell et al. 1995) for the atmosphere and oceans. The implementation in the IMAGE model is further described in Eickhout et al. (2004).

Results

Figure 1 shows that the proportion of remaining species is relatively high in temperate and boreal regions in the western and northern part of Europe, whereas in southern and south-eastern Europe the proportion is relatively low. The mitigation scenarios show higher proportion of remaining species compared to the baseline situation. The pattern of species gains, if assuming complete dispersal,

Fig. 1 Expected average percentage of stable area of 856 European plant species for the baseline scenario and two mitigations scenarios
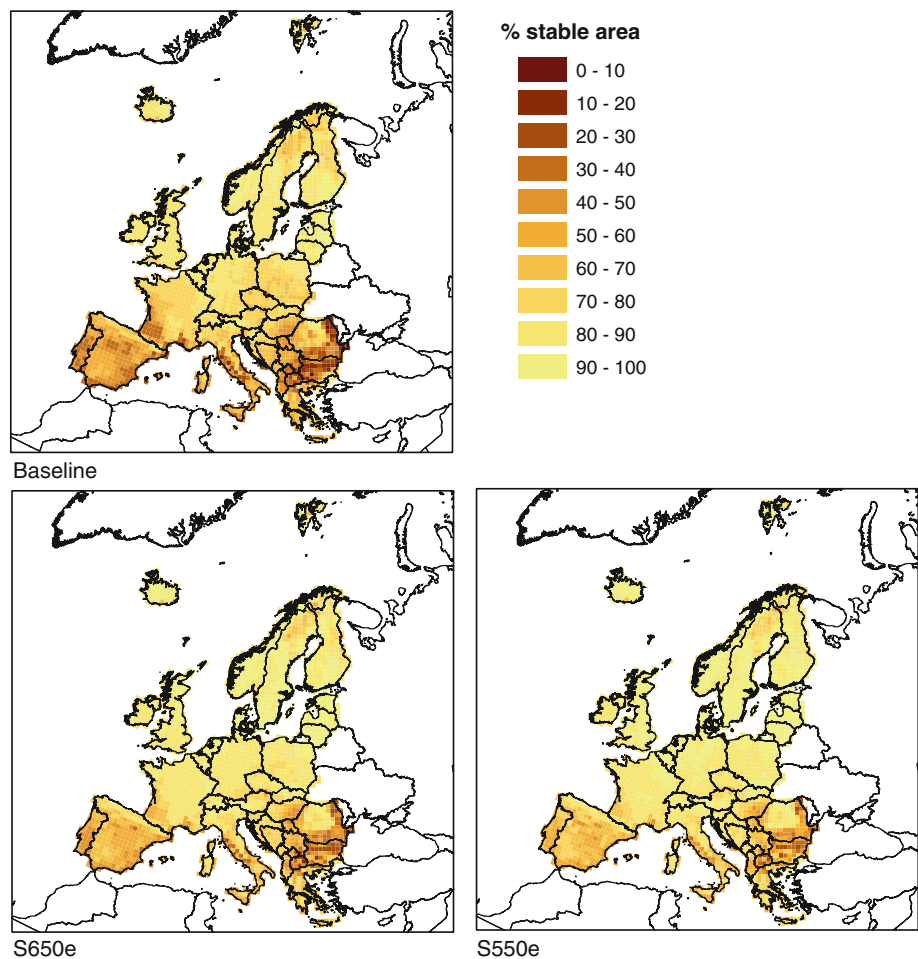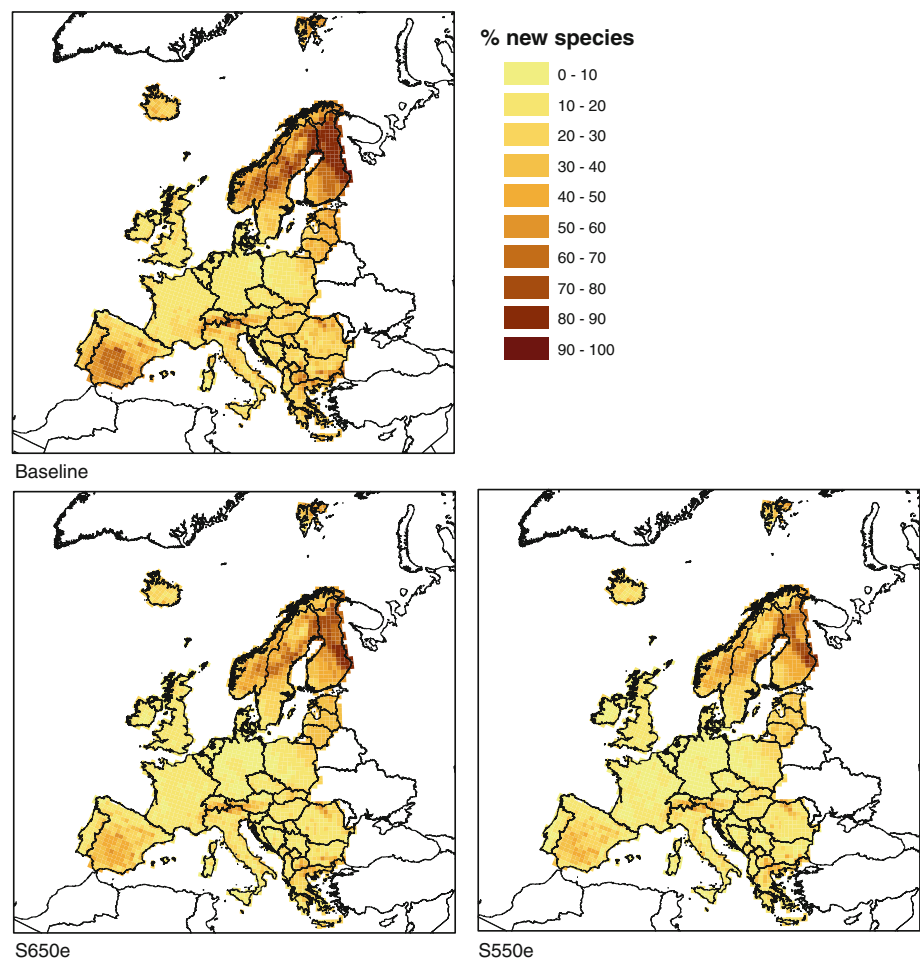
Table 1 Species gain and loss for three scenarios in each biome as a percentage of the current number of species

Biome	Current nr of species	Baseline		S650e		S550e	
		Gain	Loss	Gain	Loss	Gain	Loss
Ice	32	122	25	16	9	9	9
Tundra	168	52	14	33	13	28	14
Wooded tundra	203	61	6	45	4	38	4
Boreal forest	616	13	3	12	3	10	3
Cool conifer forest	502	17	3	14	2	12	2
Temperate mixed forest	705	12	2	10	2	8	2
Temperate deciduous forest	805	2	3	2	3	2	2
Warm mixed forest	659	10	8	6	7	5	6
Grassland/steppe	617	14	18	7	16	6	14
Scrubland	523	14	24	11	19	9	14

Fig. 2 Average proportion of new species calculated over all grid cells, using 856 European plant species, for the baseline scenario and two mitigation scenarios

shows that the northern biomes will receive many new species in comparison with the current number of species. In temperate biomes, much less species will appear, but in Mediterranean scrubland and grassland systems the species gain will be somewhat higher again, especially in the baseline scenario (Table 1; Fig. 2). The species gain in the Mediterranean region might be an underestimate since possible migration of Northern African species is not included.

Table 2 shows the mean stable areas and regression equations for each biome and each scenario. Figure 3 shows some examples of the relationship between mean stable area and GMTI. The mean stable area decreases considerably with increasing climate change. The decrease in mean stable

Table 2 Mean stable area of species per biome as a percentage of the estimated area occupied in 1995, for baseline and two climate change mitigation scenarios

Slope is the regression coefficient of the linear relationship between mean stable area and GMTI

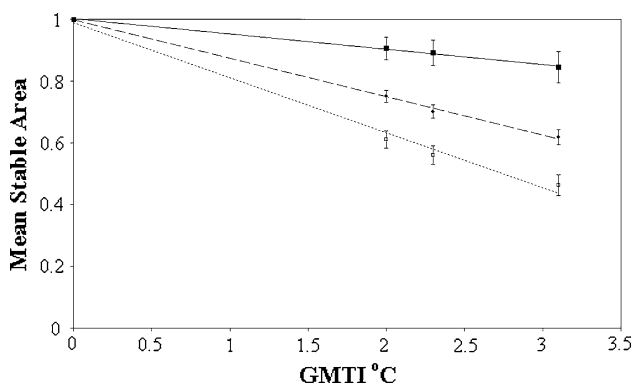| Biome	Baseline	S650e	S550e	Slope	Standard error of slope
Ice	79	82	87	−6.9	0.31
Tundra	85	89	91	−4.9	0.08
Wooded tundra	80	87	90	−6.0	0.33
Boreal forest	78	84	87	−6.8	0.15
Cool coniferous forest	77	83	85	−7.5	0.05
Temperate mixed forest	62	70	75	−12.5	0.17
Temperate deciduous forest	55	63	68	−15.2	0.50
Warm mixed forest	46	59	64	−17.7	0.13
Grassland/steppe	46	56	61	−18.3	0.56
Scrubland	46	55	60	−18.6	0.74

Fig. 3 Relationship between the global mean temperature increase (*GMTI*) and mean stable areas of species for three selected biomes. Tundra: *filled square, line*; temperate mixed forest: *filled circles, dashed line*; grassland/steppe: *empty squares, dashed line*

Fig. 4 Relationship between global mean temperature increase (*GMTI*) and turnover of species with complete dispersal $100 \times (L + G)/(N + G)$ for each biome

area seems to be linear with increasing temperature. The rate of decrease is largest in Mediterranean scrublands, grasslands and steppes and in warm mixed forests. In the colder biomes, like boreal forests, tundra and the ice biome, the decrease is estimated to be relatively low. Temperate biomes take an intermediate position.

The species turnover increases with GMTI more or less linearly, except for the Ice biome (Fig. 4). The lowest species turnover is apparently in the temperate deciduous forest biome, which is in line with patterns of stable area and species gain shown in Figs. 1 and 2. The highest species turnover occurs in the northern biomes and in the Mediterranean scrubland and the grassland systems. The turnover in the ice biome shows a steep increase between a GMTI of 2 and 3 degrees, which seems to be a turning point where climate becomes suitable for a considerable number of species. We must, however, consider that the uncertainties are high, both in climate projections as in the CEMs.

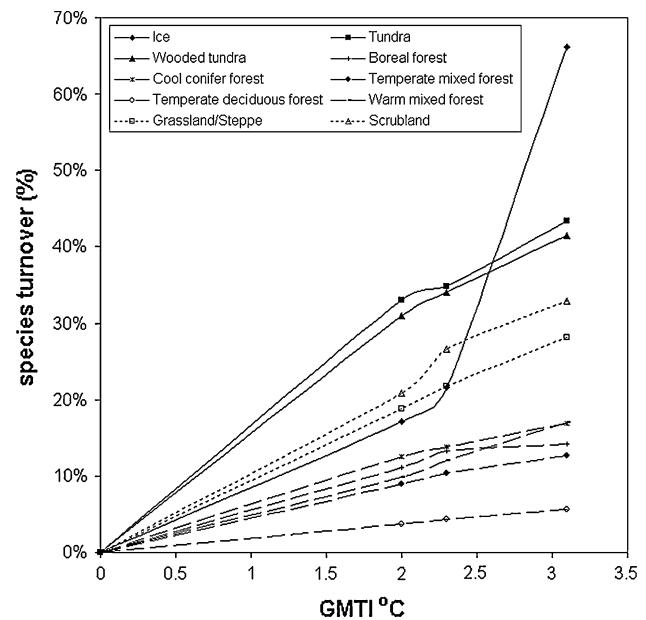The largest changes in species composition can be expected in Mediterranean scrubland and in grassland and

steppe systems. In the northern biomes like tundra and ice, the current species remain. But they might face a relatively large number of invasive species that may affect species compositions considerable. The changes tend to increase more or less linearly with GMTI, so the lower the GMTI, the lower the risk. The steep increase in species turnover in the ice biome may give a signal that unexpected large changes will be possible if temperature increases beyond a certain threshold.

Discussion

Our results show that a general relationship between relative biodiversity change and climate change can be derived

from using climate envelope models (Figs. 3, 4). These general relationships can be used to combine effects of different pressures to overall biodiversity change. These relationships can replace the expert judgments used in global and regional studies (Sala et al. 2000; Petit et al. 2001). Furthermore, the relationships based on CEMs at species level may be more indicative for biodiversity change than models at biome level (Leemans and Eickhout 2004). The relationship can be combined quantitatively with similar relationships for other environmental pressures, like nitrogen deposition and land use change (Millennium Ecosystem Assessment 2005; Scholes and Biggs 2005; Alkemade et al. 2009). Applying available relationships on certain areas may result in estimates of remaining biodiversity compared to a pristine or undisturbed situation and provides a measure for naturalness. Some results are reported in regional and global assessments (Nellemann 2004; Ezcurra 2006; UNEP 2007). In these examples, the relationship between means stable area and GMTI is used, because this was comparable to available relationships for other pressures (Alkemade et al. 2009). These applications show that the impact of climate change on global and regional biodiversity will rapidly increase towards the end of the century (UNEP 2007). The application of the relationship with species turnover will give additional insight into the impact of climate change on biodiversity.

The relationships derived in this study are far from complete and can be considered as first estimates for the European biomes, based on plant species models. Analyses based on other species groups will result in different relationships, since different patterns of species loss and species turnover are expected (e.g., Araujo and Rahbek 2006; Jetz et al. 2007). These differences need to be included in constructing general relationships. The proposed methodology can be applied to all available climate envelope models, so that a broad variety of ecosystems will be covered (e.g., Peterson et al. 2001, 2002; Beaumont and Hughes 2002; Erasmus et al. 2002; Araujo et al. 2006; Broennimann et al. 2006; Thuiller et al. 2006). The relationships can gradually be improved if more CEMs become available from other regions of the world.

Furthermore, the relationships can be improved significantly as more and different climate scenarios are used. The uncertainty can be estimated by applying different global circulation models and different modelling techniques for CEMs (Thuiller 2003; Thuiller et al. 2004; Araujo and Rahbek 2006; Bakkenes et al. 2006; Hijmans and Graham 2006). Using more scenarios also enables the verification of the linear relationship we derived in our study.

We found that a significant proportion of plant species will shift its distribution, so that the species composition of the biomes as we know them in the current state will change considerably. The mean stable area ranges from 60 to 90% in 2100 at a 2°C GMTI and from 45 to 85% in 2100 at 3°C GMTI as calculated in the mitigation and baseline scenarios, respectively. In general, these results are in line with other studies. Leemans and Eickhout (2004) calculated changes in biome areas for different global mean temperature increases. They foresee a net reduction in the ice, tundra, grasslands and scrublands biomes and increases in forested and temperate biomes. The increase in southern species in the northern biomes as predicted by our analysis might result in a biome shift in these areas. In grassland and Mediterranean scrubland in Europe, both reduction and gain of species may lead to biome shifts. Ohlemüller et al. (2006) compared climate analogues between average climate in 1931–1960 and predicted climate by 2100. They concluded that climate analogues reduce significantly in northern and central Europe and in mountain areas in southern Europe, whereas in temperate lowland areas climate analogues increase. The high risk for Mediterranean scrubland in Southern Africa is also forecasted by a study by Midgley et al. (2002). They predicted a loss of the Fynbos area of between 51 and 65%.

According to our study, the most dramatic changes will occur in Northern Europe, where more than 35% of the species composition in 2100 will be new for these regions, and in Southern Europe, where up to 25% of the species now present will have disappeared under the climatic circumstances forecasted for 2100. The predicted shift of species is in line with recent observations, showing increases in occurrence and abundance of thermophilic (heat-demanding) species and decreases in traditionally cold-tolerant species (Walther et al. 2002; Parmesan and Yohe 2003; EEA 2004, 2008; Parmesan 2006; Gregory et al. 2009).

The calculated effects of climate change are only based on average climate characteristics; timing, extremes and amplitude are not taken into account. The results of this study are therefore not complete. Many uncertain responses can be expected to occur, at least on local scales if, for example, there are extremely long drought periods or concentrated rainfall into a few weeks. We expect these extreme events to possibly worsen the effects in most cases, thus underlining the importance of stabilizing global CO_2 concentrations and additional biodiversity management measures.

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