CRITICAL ECOSYSTEM PARTNERSHIP FUND

Climate Change Portfolio Review

Literature Review and Evaluation Matrix

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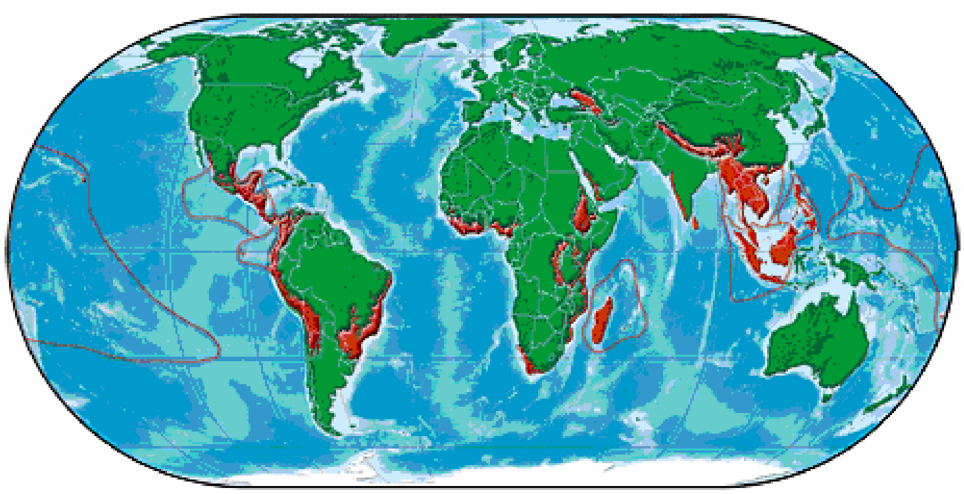

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Introduction

Anthropogenic climate change is already having demonstrable impacts on Earth's biological systems and the services they provide (Parmesan and Yohe 2003, Root et al. 2003, Parmesan 2006, Fischlin et al. 2007). The majority of observed impacts involve shifts in species' geographical ranges or their phenology, i.e. the timing and duration of events such as migration, flowering, and growing season (Parmesan and Yohe 2003, Root et al. 2003, Parmesan 2006, Fischlin et al. 2007). However, extinctions of species (Pounds et al. 2006) and populations (Parmesan 1996) have already occurred as a result of climate change, and may be vastly under-acknowledged due to a lack of appropriate sampling or attribution (Thomas et al. 2006). Some research has estimated that 25-37% of species may face extinction under mid-range climatic warming (Thomas et al. 2004), implying that climate change may be a more serious threat to biodiversity than habitat loss or other drivers of global change. While other analyses have concluded that habitat loss is likely to remain the most prominent threat in the near term, they have generally confirmed that climate change poses a significant danger to many species (Sala et al. 2000, Jetz et al. 2007).

While complete loss of suitable climatic space (within dispersal distance of current distributions) or other direct impacts threaten some species, many more may be threatened by altered ecological interactions (Parmesan 2006, Root and Schneider 2006, Thomas et al. 2006). For example, climate change-related reductions in prey availability have been implicated in declines of polar bears and penguins (Parmesan 2006). Similarly, changes in the abundance of host plants, pollinators, seed dispersers, competitors, parasites, or diseases and their vectors could all contribute to species vulnerability; multifactor extinctions due to altered ecological interactions could be the norm (Thomas et al. 2006). Importantly, our ability to predict the outcome of species interactions is inherently limited, as climate change will result in species assemblages with no contemporary or historical analogs to provide empirical guidance (Root and Schneider 2006).

The complexity of predicting climate change impacts is well illustrated by the recent loss of many neotropical amphibian species. Pounds et al. (2006) demonstrated a clear connection between warming trends and extinction of harlequin frog species throughout the American tropics. The proximate cause of extinction was likely a climate-triggered chytrid fungus epidemic. The growth of the fungus had previously been constrained by low nighttime temperatures at high elevations and high daytime temperatures at low elevations (Pounds et al. 2006). Climatic warming in the region has led to increased cloud cover, which simultaneously impedes solar radiation during the day and reduces heat loss at night. Thus, maximum daily temperatures have decreased (or increased only slightly) while minimum temperatures have increased in the region (Pounds et al. 2006). As a consequence, the geographic distribution of optimal thermal conditions for the fungus has shifted to coincide with the ranges of many of the frog species, resulting in massive losses (Pounds et al. 2006). Thus, climate change altered species interactions leading to extinctions rather than proximately causing them, and, importantly, the relevant climatic factors were related to higher-order changes in weather patterns not mean temperature increases. The implication is that fine-scale predictions about climate changes and species interactions are required to comprehensively assess climate change vulnerability.

Current modeling and empirical data may be insufficiently detailed to provide a complete picture of vulnerability, but much can still be inferred about likely climate change risks and their distribution among species and geographic regions. This report attempts to briefly summarize what is currently known about climate change risks to biological systems and possible responses to promote resilience and adaptation. It is organized in the following sections: 1) introduction, 2) projected climate changes, 3) vulnerable regions and ecosystems, 4) vulnerable species, 5) actions that promote resilience, and 6) introduction of a method to assess project relevance to climate change. Current knowledge of potential climate change impacts can provide a useful guide for conservation strategies, but uncertainties still abound. Prudent decision making and planning for climate change must account for this uncertainty.

Description of climate change

Species are sensitive to the average climate, its variability (Boyce et al. 2006), and its temporal pattern (Morales 1999), all of which are projected to change. Annual global mean temperature is projected to increase from approximately 1 °C to more than 6 °C (IPCC 2007) by the end of the 21st century, depending on emissions scenario and climate model used. The variability between emissions scenarios is typically less than the variability between climate models within a particular scenario (see figure 1). Projected mean temperature changes are not evenly distributed around the globe (see figure 2) with far northern latitudes generally expected to have greater increases than lower latitudes. While the models differ in the magnitude of projected changes in a given region, there is generally good agreement on the direction of temperature changes. Similarly, temperature changes are not evenly distributed among seasons (see figure 2). It is notable for example that winter temperatures at far northern latitudes increase more than summer temperatures.

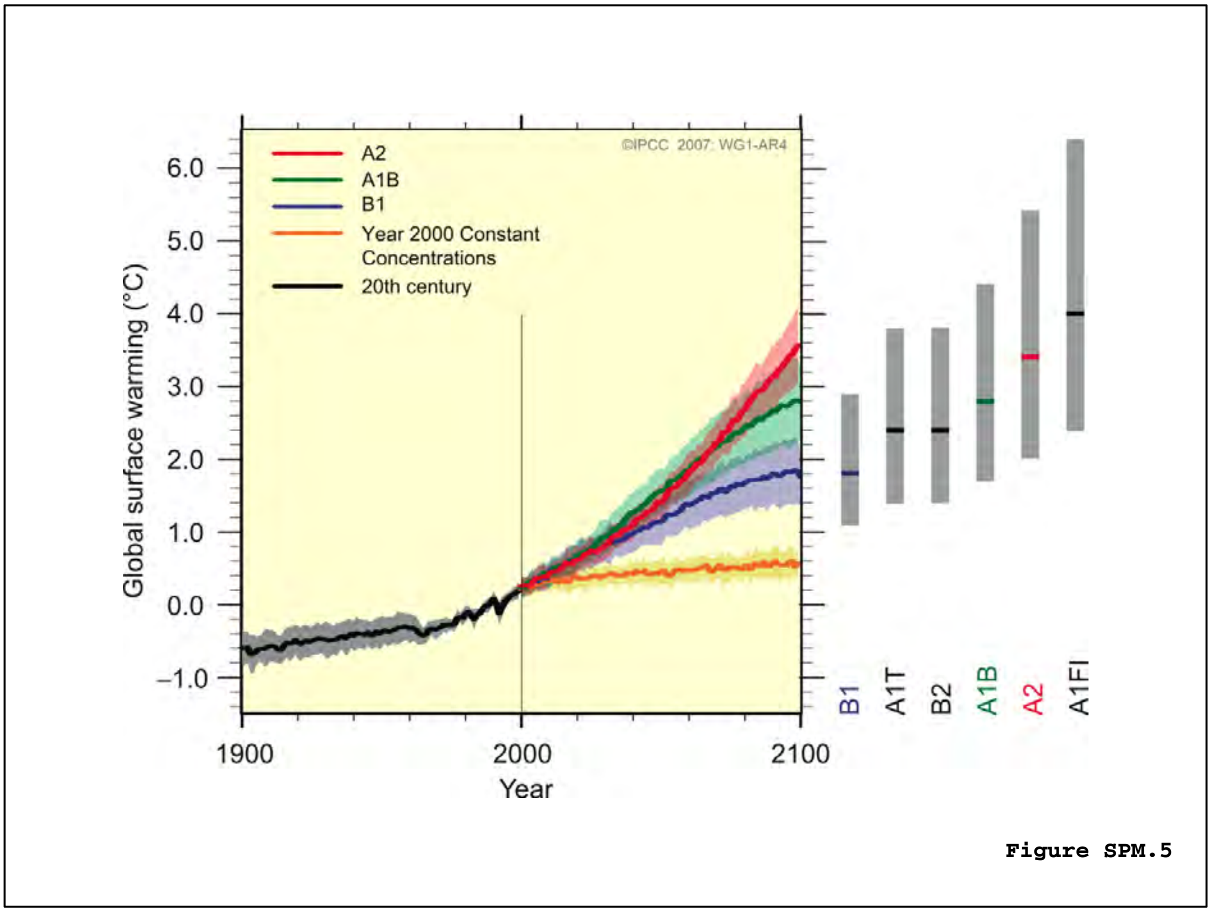

Figure 1. Projected changes in global mean temperature for different scenarios. Reprinted from IPCC (2007).

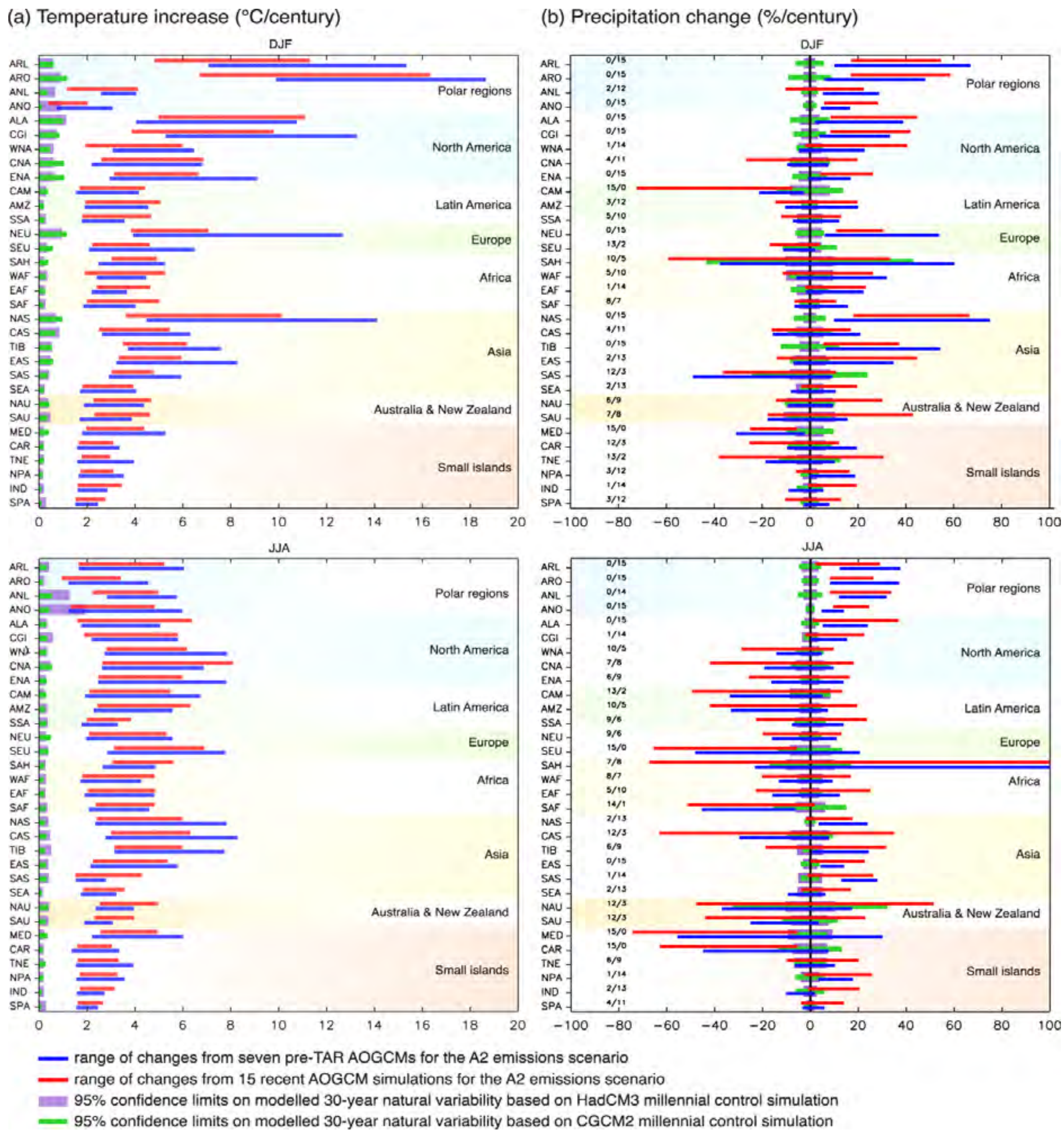

Figure 2. Range of projected changes in seasonal temperature and rainfall in different regions for different climate models. In the rainfall figures, the numbers in the graph represent the number of models predicting declines / number of models representing increases. Reprinted from IPCC (2007).

Global precipitation patterns are also expected to change considerably. Increases are generally expected for high latitudes and decreases are expected for most subtropical land areas (IPCC 2007), although there is much less model agreement on the direction and magnitude of changes for most regions (see figure 2). Importantly, the intensity, frequency, and geographic distribution of severe weather events, such as tropical cyclones and hurricanes are also expected to change (Emanuel 2005, Hoyos et al. 2006, IPCC 2007). Additionally, changes in precipitation and temperature will also lead to changes in natural disturbance regimes like floods and fires (Scholze et al. 2006, Fischlin et al. 2007, Alo and Wang 2008).

Many climatic variables exhibit extremely long-lived autocorrelations (Koutsoyiannis 2006) and as a consequence extreme events are likely to be followed by additional extreme events (Eicher et al. 2007), thus phenomena like heat waves and drought are expected to become more common (IPCC 2007) as global averages change.

Additionally, mean sea level is predicted to rise up to 0.6 meters by 2100 even excluding rapid changes in ice flows (IPCC 2007). Incidences of extreme high sea levels (e.g. storm surges) are also predicted to increase due to interactions with extreme weather events. The extent of global sea ice, glaciers, and snow pack will continue to decline as the climate warms (IPCC 2007). Additional changes due to disruptions of climate teleconnections such as the Gulf Stream and the El Nino Southern Oscillation have been proposed, but there is less scientific confidence in these predictions.

As illustrated by the example of neotropical frog species, aspects of climate change relevant to biological systems are not always well known a priori nor are they necessarily the most obvious or aggregated metric. However, in recent years, increasing numbers of studies have made significant progress in linking changes in climate to potential biological impacts, which is the focus of the next two sections.

Locations and habitats vulnerable to climate change impacts

There are several recent studies that attempt to predict the global distribution of biological impacts of climate change (see Table 1). Interestingly, there are few studies that infer differential vulnerability from the geographic distribution of climate change *per se* (e.g., Williams et al. 2007). Most spatially explicit global assessments employ potential or dynamic global vegetation models (DGVMs) that project relatively coarse changes in biome distributions based on physiological responses of idealized plant functional types (e.g., broadleaf evergreen trees, C_3 grasses, C_4 grasses, etc.) to climatic variables; some DGVMs

Analysis	Results	GCMs	Scenarios	DGVM	Notes
Climatic change per se					
Williams et al. (2007)	Disappearing climates: Columbian and Peruvian Andes, Central Africa, African Rift Mountains, Zambian and Angolan Highlands, Cape Province, southeast Australia, portions of the Himalayas, Indonesian and Philippine archipelagos, some circum-Arctic regions. Novel climates: Amazonia, Indonesian Rainforest, western Sahara, low-lying portions of east Africa, eastern Arabian Peninsula, southeastern U.S., eastern India, southeast Asia, northwestern Australia	CCSM, CSIRO, ECHAM, GFDL, GISS, IPSL, CGCM, PCM, UKMO-Had3	A2, B1	N/A	Used multidimensional distance between modern and future climates to determine where novel and disappearing climates are distributed. Also looked at analyses limiting search for analogs to within 500km, which drastically increased spatial extent to include large parts of Asia, SE USA, Europe.
Biome distribution shifts					
Malcolm et al. (2002a, 2002b, 2006)	Far northern latitudes, Australia and New Zealand, southern Africa, northeastern India, southwestern South America.	HADCM2GHG, HADGCM2SUL, GFDL-R30, GISS, OSU, UKMO, MPI-T106	2xCO_2	BIOME3, MAPSS	Considering just biodiversity hotspots: California Floristic Province, Cape Floristic Region, Polynesia and Micronesia, Southwest Australia, Caribbean, Indo-Burma, Mediterranean Basin, New Caledonia, New Zealand, Mountains of South Central China, Succulent Karoo, Tropical Andes
Leemans & Eickhout (2004)	Eastern Amazon, grasslands and deserts in Mexico, Southeast Asia, Western India, Himalayan plateau region, Mediterranean habitats, Europe, Northern latitudes	Not reported	1,2,& 3°C mean rise by 2100	IMAGE (BIOME)	Used multiple GCMs and SRES scenarios implemented by IMAGE team
Lucht et al. (2006), Schapoff (2006), Fischlin (2007)	Northward expansion and southward contraction of evergreen boreal forests, disappearance of tundra in NA and Eurasia. Increase in evergreen vegetation in SE USA, eastern China. Savannahs and woodlands of South America and Southern Africa have increased woody cover. Eastern edge of Amazon reduces evergreen cover.	ECHAM5, HadCM3	A2, B1	LPJ-DGVM	Had 1 high warming (HadCM3-A2) and one mid warming scenario (ECHAM5-B1). Biomass (carbon stored) in Amazon decreased strongly even though plant functional types did not necessarily change.

Analysis	Results	GCMs	Scenarios	DGVM	Notes
Scholze et al. (2006)	Arctic and boreal zone (esp. southern Siberia, Russian Far East, western interior of Canada - lower probability in eastern China), Central America, Amazonia, Gulf Coast of the US. Some conversion to forest in sub-Sahara and basically circum-Congo, Chile, Southeast Australia and far north Australia, south India	CGCM3.1, CNRM-CM3, CSIRO-Mk, GFDL-CM, GISS, IPSL-CM4, MIROC3, ECHAM5, MRI, CCSM3, PCM, HadCM3	A2, B1	LPJ-DGVM	Grouped model outcomes according to degree of warming predicted <2, 2-3, >3. Just looked at forest to non-forest transitions, as well as run-off and fire frequency
Alo & Wang (2008)	Expansion of boreal forests in northern latitudes, vegetation degradation in tropics, particularly parts of West and South Africa, and South America	CCSM, GFDL, GISS, HadCM3, ECHAM, MIROC, CGCM, FGOALS	A1B	CLM-DGVM	Compared differences between A1B and a pre-industrial control. Models were initiated with bare ground and apparently run until near equilibrium
Species range changes					
Jetz et al. (2007)	Large species range losses due to climate change at high latitudes. Under optimistic scenarios climate change accounts for approximately 50% of range losses at tropical latitudes, while under more pessimistic scenarios absolute range loss due to climate is greater, but proportionally it is less due to increased land conversion.	Not reported. Relied on MEA analyses.	MEA scenarios	IMAGE (BIOME)	Analysis for birds. Relies on the Millennium Ecosystem Assessment scenarios, GCM and DGVM implementations. Ranges were assumed static and biome changes due to climate change or land conversion are considered lost.

Table 1. Summary for global studies of biological impacts of climate change.

additionally incorporate competition between functional types and responses to disturbances such as fire. An alternative to DGVM-based approaches is to essentially sum individual species responses, although this is particularly data intensive and impractical in most circumstances. Jetz et al. (2007) did explore the global response of birds, which is perhaps the most well known taxonomic group, but the impacts on bird distributions were actually inferred from DGVM-predicted biome changes rather than directly modeled as functions of climatic variables.

As previously discussed, changes in climatic variables are not distributed uniformly in space or time. Williams et al. (2007) simultaneously considered seasonal values of temperature and rainfall (normalized by their inter-annual variability) to map the distance between current and projected future climatic conditions (see figure 3). Perhaps the most surprising result is that tropical regions are extensively impacted by climate change. Far northern latitudes are also projected to be heavily impacted, although not as extensively as naively expected based on the magnitude of projected changes (e.g., see figure 2). The projected changes at northern latitudes, while large in absolute magnitude, are relatively smaller compared to their current variability than are changes in tropical regions where inter-annual variability is generally much lower (Williams et al. 2007). Thus, many tropical species are expected to encounter climatic conditions considerably different than today and that are outside of the normal range of climatic variability they currently experience.

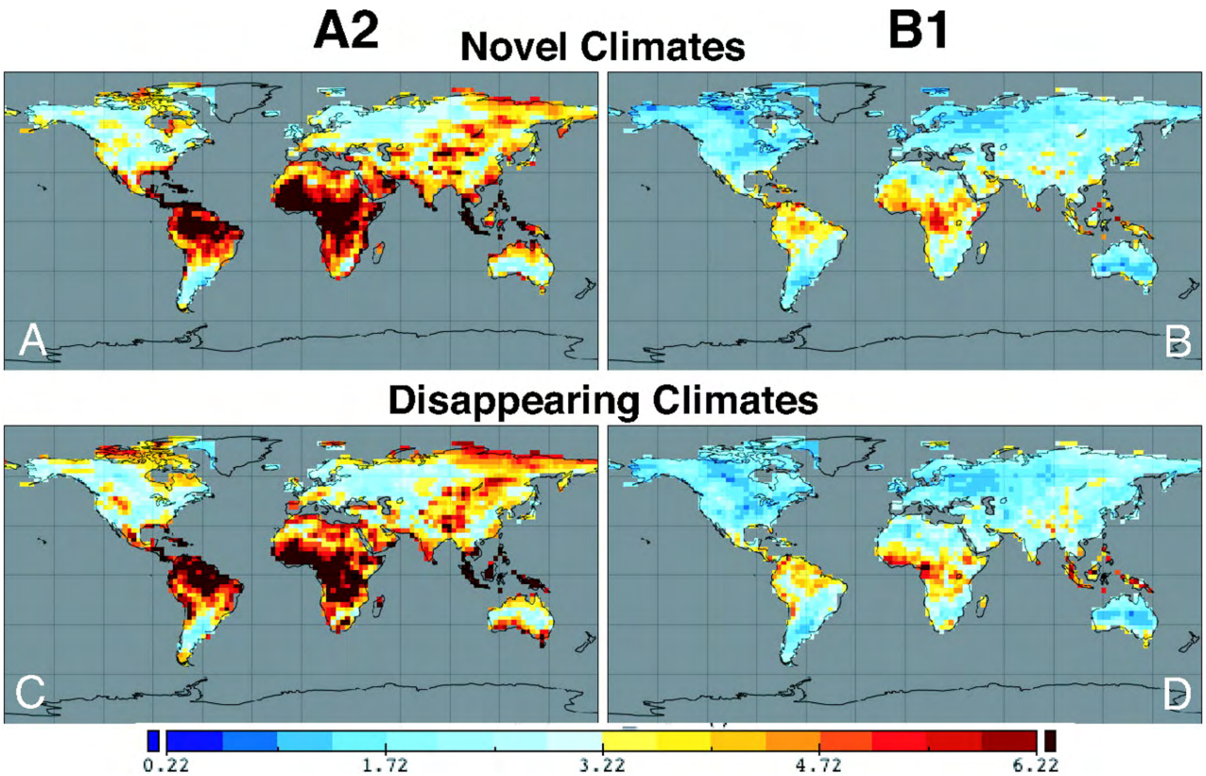

Figure 3. GCM ensemble projections of novel and disappearing terrestrial climates by 2100. (scenarios A2 and B1). Color scale indicates the minimum standardized Euclidean distance between future and current climate (A & B) or between current and future climates (C &D); yellow and red indicates greater distance. Only climates within 500km radius of a grid cell were considered when assessing distances. Reprinted from Williams et al. (2007).

Looking across the available DGVM studies, it is clear that there are significant differences in expectations of vulnerability based on the climate model, emissions scenario, and vegetation model used. However, there are also some surprisingly consistent findings about broad scale geographic patterns of vulnerability (see Table 1, and Appendix A for maps from individual studies) despite different modeling techniques and assumptions. Far northern latitudes, including parts of Russia, Scandinavia, Canada, and Alaska are consistently projected to experience significant changes in vegetation. In part this reflects the larger projected increases in temperatures at northern latitudes compared to other regions and the consistency among available climate models in the direction of predicted precipitation changes. Tropical regions are also expected to be particularly hard hit with eastern Amazonia, Mesoamerica, Southeast Asia, and central Africa routinely identified as vulnerable. Portions of southern India, the Himalayan region, the southeastern portion of the United States, the Mediterranean Basin, parts of Australia, parts of Chile and Argentina, as well as parts of southern Africa are also projected to experience significant change in several studies (see Figure 4 for an example map).

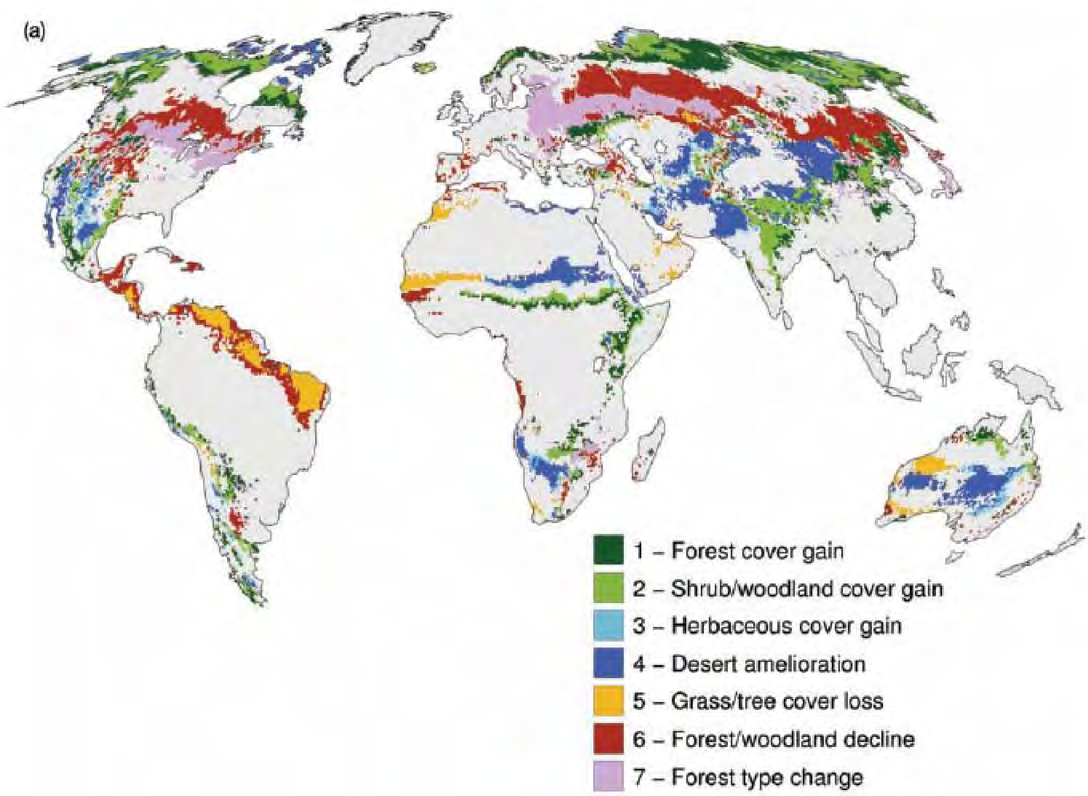

Figure 4. Projected changes in terrestrial biome by 2100 under HadCM3 (scenario A2). Only changes exceeding 20% of the area in a grid cell are illustrated. Reprinted from Fishlin et al. (2007).

The broad regional patterns of vulnerability inferred from the coarse global analyses are confirmed and refined by more regional analyses where available. Additional details about vulnerable landforms and ecosystem types can also be identified, including sea ice biomes, tropical forests, particularly cloud forests and dry forests, mountainous regions, Mediterranean-type ecosystems, coastal areas, and island ecosystems.

As noted above, far northern latitudes are expected to undergo significant climatic changes, as are high southern latitudes. Sea-ice biomes in particular are expected to be especially sensitive (Fischlin et al. 2007), with biological impacts already noted for populations of krill and several penguin species in the Southern Hemisphere and polar bears and ringed seals in the Northern Hemisphere (Parmesan 2006). In addition, tundra ecosystems are especially vulnerable due to melting permafrost, reduced climatic barriers to invasive or expanding species, and limited opportunity for poleward range shifts. While generally considered species-poor, especially compared to tropical regions, it is notable that nearly 15% of bird species worldwide breed in Arctic tundra (Wormworth and Mallon 2006); significant losses of range are predicted for birds at far northern latitudes (Jetz et al. 2007).

While tropical regions are not predicted to have mean temperature changes as large as higher latitudes, tropical vegetation is particularly sensitive to water balance. For example, the Amazon is considered at risk for 'savannization' even under current climatic conditions due to the frequency of seasonal drought, with fire as a likely proximate driver of conversion from evergreen forest to savannah (Oyama and Nobre 2003, Hutyra et al. 2005). Janzen (1967) famously proposed that the relatively low daily and monthly climatic variability in tropical regions has led to narrowly-adapted species, suggesting that relatively small changes in climate could push species outside of their physiological tolerances. Additionally, endemic diversity is concentrated in areas that have experienced lower climatic variability during the last 2 million years, suggesting that climatic stability has been a key factor in supporting biodiversity (Fischlin et al. 2007). It has been noted that tropical regions typically have limited technical and financial capacity for management and adaptation to changing climates (Hannah et al. 2002a). The vulnerability of tropical regions is underscored by the fact that climate change has already been linked to species extinctions in some tropical locations (Pounds et al. 2006). Within the tropics, cloud forests (Still et al. 1999) and dry forests (Miles et al. 2006) have been suggested to be particularly vulnerable to changing climates.

Regardless of region, there is strong evidence that mountainous areas and montane species are particularly vulnerable to climate change (Malcolm et al. 2002a, Thuiller et al. 2005, Wilson et al. 2005, Fischlin et al. 2007, Marris 2007, Sekercioglu et al. 2008). This is largely due to the natural limit to upward migration imposed by mountain tops as well as the reduction in available area at higher elevations (Pounds and Puschendorf 2004, Sekercioglu et al. 2008).

Mediterranean-type ecosystems, which are characterized by wet winters, dry summers, and generally shrubby vegetation, are also predicted to be sensitive to climate change (Fischlin et al. 2007, Thuiller 2007), largely due to changes in water balance and limited natural capacity to adapt given existing and projected patterns of development (Fischlin et al. 2007). The extensively studied Cape Floristic Region in South Africa contains prominent examples of Mediterranean-type ecosystems that are projected to be severely impacted under climate change (Midgley et al. 2003, Bomhard et al. 2005, Hannah et al. 2005, Pyke et al. 2005, Midgley et al. 2006).

Coastal wetlands (e.g. mangroves and salt marshes) (Davis et al. 2005, Gilman et al. 2006), mudflats, and river deltas (Fischlin et al. 2007) are also considered to be particularly vulnerable to climate change due to several interacting effects of climate change. Sea level rise will directly inundate coastal wetlands, which will be lost if they cannot migrate inland due to topography or human development (see Figure 3). Greater storm intensity predicted under climatic warming (e.g., Emanuel 2005, Hoyos et al. 2006) will additionally lead to higher storm surges resulting in salt water intrusions and increased coastal erosion. Altered precipitation patterns and runoff (Scholze et al. 2006) will also affect freshwater inflows to coastal wetlands, as well as the input of terrestrially-derived nutrients and sediments. Islands are likewise predicted to be vulnerable to the combination of sea level rise and increasing storm intensity. Additionally, islands have limited opportunities for organisms to disperse to climatically suitable areas due to their limited size and isolation. Island populations also tend to be small and less genetically diverse than continental counterparts, potentially increasing their vulnerability.

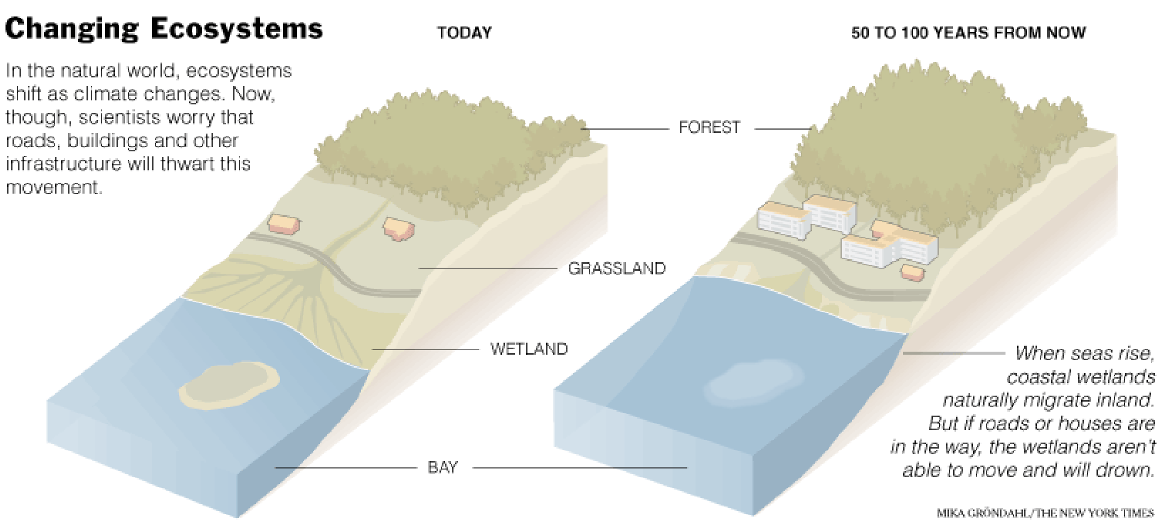

Figure 5. Illustration of coastal wetland loss with sea level rise. Reprinted from Dean (2008).

Species sensitive to climate change

The vulnerability of individual species to climate change is increasingly being documented (e.g., McMahon and Hays 2006, Foden et al. 2007), but general predictors of species vulnerability might be more useful in conservation planning. Identifying common traits that confer, or at least correlate with, vulnerability to climate change is hindered by the fact that species are expected to respond individualistically to climate change (Parmesan 2006, Root and Schneider 2006). Despite this limitation, several important species traits have been identified, although some are awaiting further empirical validation (a list of proposed traits being investigated by the IUCN (Foden and Collen 2007) is given in Appendix B).

Restricted or limited geographical range has been proposed as a factor in species' susceptibility to climate change (IUCN 2003, Schwartz et al. 2006). Restricted range is considered a risk factor in assessing conservation status irrespective of climate change (IUCN 2001), and poor conservation status (including small population size, low genetic diversity, and existence of other threats) is likely to increase climate change vulnerability. Similarly, limited elevational (Sekercioglu et al. 2008) or latitudinal range (Julliard et al. 2004) has been used to infer vulnerability to climate change. However, from a purely theoretical standpoint it is unclear that geographical (including elevational and latitudinal) range extent is a consistent species' trait. The geographic range of a species can be viewed as an emergent property of species' physiological constraints, ecological interactions (with resources, competitors, predators, and diseases), demography, and history. Thus, a restricted range may just be a proxy for other factors that contribute to contemporary or future vulnerability. For example, physiological tolerances such as limited thermal range (IUCN 2003, Jiguet et al. 2006) and low thermal maxima (Jiguet et al. 2007) contribute to species vulnerability to climatic warming. Similarly, metabolic performance in relation to temperature is strongly associated with range size in some taxa (Bernardo et al. 2007) and provides a mechanistic basis for inferring responses and vulnerability to climate changes (Bernardo and Spotila 2006, Bernardo et al. 2007, Buckley 2008).

Ecological interactions such as extreme habitat specialization or tight dependence on other species or coevolutionary relationships are also indicative of vulnerability to climate change (IUCN 2003, Foden and Collen 2007). The physiological constraints and climatic requirements of interacting species are not perfectly correlated; species will respond individualistically (Parmesan 2006, Root and Schneider 2006). Analysis of historical ecological communities confirms that species assemblages have not remained intact as relatively discrete units but have been continuously reshuffled in response to past climate changes (Huntley 2005). Considering contemporary climate changes, in 7 of 11 cases analyzed interacting species responded differently to climate change (Parmesan 2006). As an extreme example, a plant might be driven to extinction by loss of its obligate pollinator even though the plant's climatic tolerances might not be exceeded.

Demographic factors such as reproductive output, generation time, and dispersal have all been implicated in species vulnerability to climate change (Foden and Collen 2007, Jiguet et al. 2007), they are also key parameters in source-sink dynamics, which can explain geographic distributions (Lawton 1995). Interestingly, in a study of European birds Jiguet et al. (2007) reported a positive association between reproductive output, which they also considered to be associated with shorter generation times, and climate sensitivity, which is contrary to other analyses (Foden and Collen 2007). This difference may be due to differences in definitions of reproductive output, but also highlights an important research question. The analysis of Jiguet et al. (2007) did confirm the important role of dispersal in resilience to climate change, which has been highlighted in numerous other studies (e.g., Malcolm et al. 2002b, Thomas et al. 2004, Midgley et al. 2006, Pearson 2006, Foden et al. 2007). Interestingly, having a single clutch in a year was found to increase risk, potentially due to the mistiming of reproduction with respect to peak food abundance (Jiguet et al. 2007), which has been reported in other studies (Thomas et al. 2001, Visser et al. 2004). More generally, reliance on climatic cues for timing of life-cycle events, such as reproduction or migration, is presumed to increase vulnerability to climate change (Foden and Collen 2007). Additionally, long-distance migrants are expected to be particularly vulnerable to climate change due not just to issues of timing (Both and Visser 2001, Both et al. 2006) but to potential habitat changes in breeding grounds, over-wintering areas, and migratory stopover sites as well as the increasing frequency of severe weather events en route (see Wormworth and Mallon 2006 for a review).

For particular regions and taxonomic groups, e.g. plants in the Cape Floristic Region, Australian birds, or Mexican butterflies, it might be possible to develop a ranked list of vulnerable species. Unfortunately, data for these regions while extant are not always publicly available. Identities of additional vulnerable species can be culled from the ecological literature, but relative rankings of species are not possible from this type of ad hoc analysis.

Actions that promote resilience and adaptation

While mitigation of climate change is necessary to meet many conservation targets, there is increasing emphasis on developing effective strategies to promote the resilience of ecological systems and aid in their adaptation to novel and changing climates (Hannah et al. 2002a, Hannah et al. 2002b, Hansen et al. 2003, Hannah et al. 2007, Dean 2008). The good news is that numerous new and existing strategies have been proposed in response to the challenge of conserving biodiversity in a changing climate. Strategies can broadly be categorized into actions that 1) protect appropriate places, 2) limit non-climatic stressors, or 3) manage adaptively.

Protect appropriate places

Additional area will need to be protected to accommodate changing species distributions and ecological interactions (Hannah et al. 2002b, Hannah et al. 2007). When selecting sites for preservation under climate change, traditional conservation considerations carry additional gravitas. All else being equal, larger reserves and more well-connected networks are expected to perform better under climate change (Hansen et al. 2003), particularly if sites are chosen in the context of a strategic, regional planning effort that sets guidelines for compatible and complimentary uses in non-protected areas (Hannah et al. 2002b, Da Fonseca et al. 2005, Hannah and Hansen 2005). The establishment of buffer zones and corridors (Hannah et al. 2002b, Hansen et al. 2003) is expected to be beneficial as organisms disperse to climatically suitable areas. Redundancy, or multiple representation, of species (Hannah et al. 2002b) within protected area networks may increase the likelihood that at least some populations persist. Likewise, ensuring that topographic, environmental, and microhabitat heterogeneity (Hansen et al. 2003), as well as genetic diversity (Lovejoy 2005, Reusch et al. 2005, Willi et al. 2006) are represented within reserve networks might allow populations to shift their distributions or adapt in situ in response to climatic changes. It has been suggested that conservation planning in general should focus on the preservation of dynamic biodiversity processes (Pressey et al. 2007), which might focus attention on keystone species or maintenance of functional groups (Hansen et al. 2003).

In addition to spatial strategies that are widely applicable irrespective of climate change, several more tailored approaches have been suggested. One example is moveable reserves (Pressey et al. 2007) that can track features of interest, although implementation is likely to be difficult in terrestrial systems (Pressey et al. 2007). Li et al. (2006) proposed that (fixed) reserves should be expanded poleward or along elevation gradients to accommodate probable range shifts without making reference to particular species. However, the sophistication and refinement of reserve site selection approaches to consider future species or biome distributions and representation of bioclimatic factors has markedly increased in recent years (Hannah et al. 2002b, Araujo et al. 2004, Coulston and Riitters 2005, Hannah and Hansen 2005, Pyke et al. 2005, Pyke and Fischer 2005, McClean et al. 2006, Hannah et al. 2007). There have similarly been significant improvements in planning climate change specific dispersal corridors (Da Fonseca et al. 2005, Williams et al. 2005).

Aside from methodological improvements in selection algorithms, additional spatial conservation priorities have been proposed. Climatic refugia (Hannah et al. 2002b, Saxon et al. 2005), which will experience less dramatic abiotic changes, are likely to be important for the persistence of some species. Additionally, outlier populations, populations on the fringes of current species ranges, or which occur in less climatically suitable space are likely to be important as dispersal kernels (Pearson 2006), as sources of genetic diversity and evolutionary processes (Hampe and Petit 2005), or simply because suitability might increase as climate changes (Hannah et al. 2002b). Another important conservation target is upland areas specifically to allow for landward migration of wetlands as sea levels rise (Dean 2008).

Limit non-climatic stressors

The ability of ecosystems and species to respond to perturbations depends on their current state. Species pushed to the brink of extinction by various stressors may be unable to cope with a rapidly changing climate. Thus, reducing non-climatic stressors is a potent strategy to maintaining the resilience of ecosystems to climate change (Hannah et al. 2002b, Hansen et al. 2003). Potential non-climatic stressors include habitat loss and fragmentation, anthropogenic disturbance, harvesting and exploitation, pollution, invasive species, freshwater diversions and groundwater pumping, and epidemic disease or parasites. While all stressors are potentially synergistic with climate change in the sense that the combined impacts are greater than the sum of the impacts applied singly, there are clearly mechanistic interactions of some stressors with climatic processes. Fragmentation, by definition, reduces connectivity and thereby hinders species dispersal (Pearson and Dawson 2005, Root and Schneider 2006) and ability to track suitable climates across a landscape. Drying at fragment edges will exacerbate water stress caused by precipitation declines and elevated temperatures, while exposure to anthropogenic ignition sources could lead to more intense or frequent fires and rapid biome conversion in some tropical areas (Hutyra et al. 2005). Likewise, freshwater diversions could exacerbate drought stress caused by precipitation declines and groundwater pumping could lead to subsidence of deltas and coastal wetlands (Dudley 2003) effectively amplifying the effects of sea level rise.

The options to reduce non-climatic stressors depend on the nature of the stressor and the context, precluding general strategies. It should be noted, however, that potential strategies may fall outside the purview of traditional conservation approaches. For example, increasing agricultural yields, purchasing water rights, or providing alternative water supplies to developing communities may significantly reduce human demands on ecosystems (Fischlin et al. 2007). Similarly, ecosystem service payment approaches may also be useful in this regard.

Manage adaptively

Management activities, analogous to spatial considerations, can heuristically be divided into practices that promote adaptation or resilience to climate change, but are generally beneficial irrespective of climate change, and practices that are more narrowly focused on climate impacts. For example, the importance of regional conservation planning is greatly increased when considering climate change. As populations migrate and respond to climate signals, cooperation and coordination of management objectives and activities across institutional and geographic jurisdictions is key to success. Management should be adaptive with sufficient monitoring and evaluation to guide future decisions.

Just as effective management should extend across jurisdictions, it should also extend beyond reserves and protected areas to encompass the landscape matrix surrounding reserves.

Low-intensity and biodiversity friendly practices (e.g., agroforestry) should be identified and promoted. While regulatory mechanisms restricting particular land-uses or practices might be effective in some circumstances, incentive-based mechanisms such as ecosystem service payments are also possible. Where appropriate legal and institutional frameworks exist, easements or fee purchase of particular rights (e.g., grazing or development rights) might also be effective mechanisms to encourage biodiversity friendly uses outside of reserves. Interfacing with private landowners and communities requires institutional capacity to develop and maintain relationships, with trust being particularly important, yet difficult, to establish. Broad cooperation might require ceding some decision-making authority or ownership to communities (Fischlin et al. 2007).

Habitat restoration is another potentially useful management action, particularly if projected areas of climatic suitability for species or biomes of interest are currently degraded. The more ambitious and prosaic concept of rewilding, which entails geographically extensive reversion of developed areas to natural land cover, might also be useful to combat losses due to climate change. Similarly, the restoration, enhancement, or replacement of degraded ecosystem services has been suggested to increase resilience to climate change (Fischlin et al. 2007). More intensive examples include, manual pollination, seed dispersal, and pest control (Fischlin et al. 2007), although maintenance or reintroduction of pollinators and long-distance seed dispersers, like birds, bats, and large mammals (Hannah et al. 2002b) may be more effective. Reintroductions of extirpated species in general, particularly top predators (Wilmers and Getz 2005), might buffer biological communities against climate change by maintaining food web structure or other ecological interactions. Ex situ management of particularly vulnerable species will continue to be a costly option, but might be necessary in some circumstances.

More tailored management responses to climate change include species translocation, or ‘assisted migration’ (Hulme 2005, Fischlin et al. 2007, Hunter 2007), habitat creation, manipulation of disturbance regimes to maintain relict populations (Hannah et al. 2002b), and conservation call options (Hannah et al. 2002b). In order to track changing climates many species will need to migrate at unprecedented rates (Malcolm et al. 2002b), particularly considering the impediments to dispersal created by human land uses, leading to the conclusion that dispersal limitation is likely to be widespread and will exacerbate range contractions for many species. Species translocation, which moves species to new and presumably suitable areas, has been suggested to be more effective for conservation than simply increasing connectivity (Hulme 2005). Likewise, habitat creation in novel areas, might promote persistence of some species and ecosystem types. Purposeful manipulation of disturbance regimes has been proposed as a technique to prevent vegetation transitions by 'natural' processes in order to retain relict vegetation types. For example, some regions are projected to lose grassland areas to woody encroachment, but this might be prevented by controlled burning or grazing. Similarly, conversion from forest to more savannah-like conditions might be prevented by fuel management and fire suppression. To address changing, and uncertain, conservation needs in the future, Hannah et al. (2002b) proposed the truly innovative idea of a conservation future agreement, which might more appropriately be termed a conservation call option. Essentially a landowner would sell an option on their land providing the right, but not the obligation, to purchase the land at a future date if it becomes valuable for conservation. Similar to conservation easements it could include restrictions on development or detrimental practices in the interim. The advantages are that landowners can generate revenue while maintaining ownership and conservation organizations can hedge against uncertainties in future species distributions and conservation requirements. The drawback is that legal frameworks and institutions for crafting and enforcing such arrangements do not currently exist.

Assessment of project relevance

The climate relevance of projects can be assessed by asking whether they address climate change vulnerabilities in ways that promote resilience and adaptation. Breaking this question into its two fundamental components, vulnerability and promotion of resilience, suggests axes along which to evaluate projects. Aspects of vulnerability can be divided into 1) geographical and ecosystem factors and 2) species factors, as discussed in sections 3 and 4 of this report. Projects can be scored according to whether they address vulnerable areas, vulnerable, hotspots or vulnerable ecosystems. The scores for each of these aspects of vulnerability are summed and normalized by the maximum possible to determine the vulnerability score for geographical and ecosystem factors (details for scoring are provide in Table 2b). Likewise, projects can be scored according to the numbers of species vulnerable to climate change, as inferred from the traits discussed above, that they address and normalized by the maximum possible points to determine the vulnerability score for species factors(details for scoring are provide in Table 2b). The overall score for how well a project addresses known vulnerabilities is a weighted average of its geographical and ecosystem factor sub-score and its species factors sub-score. Geographical and ecosystem factors are relatively unambiguous to assess and the data is more readily available than is species information, therefore the geographical and ecosystem factor sub-score is weighted to account for 80% of the total vulnerability score while the species factor sub-score is weighted to account for 20%.

Promotion of resilience can divided into actions that 1) protect appropriate places, 2) limit non-climatic stressors, or 3) manage adaptively, as discussed in section 5. Within these broad categories, a gradient from general to specific factors can be considered. Similar to the procedure for vulnerability score, a project is assigned a score for each aspect of resilience promotion with general and climate change specific actions considered separately (details for scoring are provide in Table 2c). The scores for general actions in each of the resilience promotion categories are summed and normalized to determine a general resilience promotion score. It is unrealistic to expect that a single project would effectively be able to simultaneously protect appropriate places, limit non-climatic stressors, and manage adaptively; therefore, the general resilience promotion score was normalized by factor equal to the maximum score considering just 2 of the 3 categories. In an analogous fashion, a specific resilience promotion score can be determined for each project (details for scoring are provide in Table 2c) and similarly normalized. The overall score for how well a project promotes resilience is a weighted average of its general and specific resilience promotion sub-scores; the sub-scores are equally weighted.

A sample project evaluation form illustrating this sort of evaluation is shown in Table 2a, with the details for the column headings and scoring given in Tables 2b and 2c. A sample project evaluation matrix displaying the vulnerability and resilience scores and the relative budget of the project is given in Figure 6. Note that quadrant II contains highly climate relevant projects, quadrant III contains projects with limited relevance, while quadrants I and II contain projects of moderate relevance that either promote resilience effectively or target vulnerabilities, respectively, but not both.

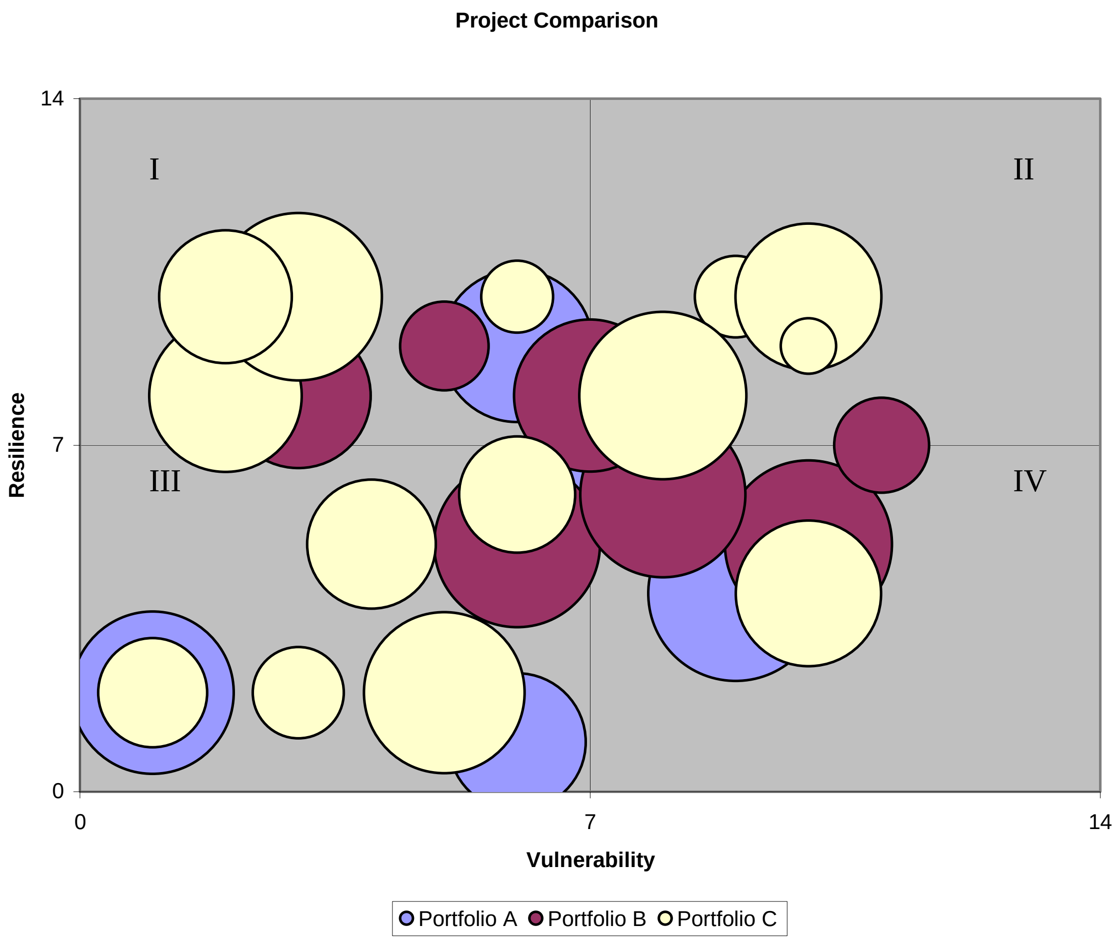

Figure 6. Project Evaluation Matrix. Colored circles indicate illustrative project distribution. Projects are plotted in Vulnerability-Resilience space according to qualitative scores determined in the project evaluation matrix. Each circle corresponds to a project, the size of the circle is proportional to a projects budget. Different colors represent different portfolios.

Project		Vulnerability					Resilience promotion						Scaled Vulnerability score	Scaled Resilience score
		Geographic/Ecosystems			Species		Area		Non-climate threats		Management			
		General --> Specific												
Name	Budget	Region	Hotspot	Ecosystems & landforms	Climate sensitive		General	Specific	General	Synergistic	General	Specific		
Bladen Nature Reserve Protection Program	--	2		3					2		1		0.50	0.25
Infrastucture Integration and Biodiversity Conservation in Mesoamerica	--	2							1		3		0.20	0.33
Baviaanskloof Mega-Reserve Project: Mega-Reserve Vision and 5-Year Development and Management Plan	--	2	3	3							3		0.80	0.25
Co-authorship of a Book Entitled: East of the Cape - Conserving Eden	--	2									1		0.20	0.08
Framework for Eco-Historical Tourism in the Sierra Madre Biodiversity Corridor	--			3							2		0.30	0.17
Building Partnerships for Sustainable Management of Critical Watersheds in the Sierra Madre's PMMR, Nueva Vizcaya, Northeastern Luzon, Philippines	--			3							3		0.30	0.25

Table 2a. Project evaluation worksheet

Vulnerability	Geographic/Ecosystems	General --> Specific	Region	Far Northern latitudes Eastern Amazonia Mesoamerica Central Africa Southern India Himalayan region South Africa Australia Southeast USA Southwestern South America	Assign 2 points
			Hotspot, Tier 1	California Floristic Province Cape Floristic Region Polynesia and Micronesia Southwest Australia	Assign 3 points
			Hotspot, Tier 2	Caribbean Indo-Burma Mediterranean Basin New Caledonia New Zealand Mountains of South Central China Succulent Karoo Tropical Andes	Assign 2 points
			Ecosystems & landforms	Sea-ice biomes tundra tropical cloud forest tropical dry forest mountainous areas Mediterranean-type ecosystems coastal wetlands (mangroves, salt marshes, mudflats) river deltas oceanic islands	Assign 3 points
	Species		Climate change sensitive species	Narrow habitat requirements or tight association with particular habitats Narrow thermal range, moisture ranges, O2 ranges, etc. Or low thresholds beyond which physiological function rapidly breaks down. Dependence on environmental triggers for life-cycle events (e.g. migration, spring emergence, breeding, etc.) Only consider cues likely to be affected by climate change (e.g. temperature or rainfall, not day length or lunar cycle). Tight dependence on interspecific interactions, e.g. sybionts, specialized pollinators/seed dispersers, host plants, narrow prey/resource range Limited ability to disperse and colonize new areas. May consider extrensic limitations to dispersal, such as geographic features (large mountain ranges, oceans) or anthropogenic transformation of migration routes	Assign 0-3 points based on relative numbers of sentsitive species as well as their vulnerability to climate change. Do not consider general risk factors like current IUCN classification or endemism

Table 2b. Description of vulnerability score assignment.

Resilience promotion	Area	General	Additional area Part of regional network Increases connectivity Buffer zones Corridors Redundancy Representation of heterogeneity (topographic, microhabitat, genetic)	Assign 0-3 points. Consider number of qualifying actions, their efficacy, and any other relevant factors
		Specific	Moveable reserves Areas chosen for future climate Corridors planned for future climate Climatic refugia Outlier populations Upland areas for wetland migration	Assign 0-3 points. Consider number of qualifying actions, their efficacy, and any other relevant factors
	Non-climate threats	General	Pollution Exploitation, harvesting	Assign 0-3 points. Consider number of qualifying actions, their efficacy, and any other relevant factors
		Synergistic	Invasive species Anthropogenic disturbance Disease & Parasites Habitat loss, fragmentation Water diversions and withdrawals	Assign 0-3 points. Consider number of qualifying actions, their efficacy, and any other relevant factors
	Management	General	Regional & trans-jurisdictional planning, coordination, & cooperation Adaptive management procedures, monitoring, and evaluation Matrix management (incentive or regulation based) Outreach and engagement with communities Habitat restoration Enhancement, replacement, or focused maintenance of ecosystem services (e.g. pollination, seed dispersal, pest control) Species reintroductions Ex situ management (captive breeding)	Assign 0-3 points. Consider number of qualifying actions, their efficacy, and any other relevant factors
		Specific	Species translocations (assisted migration) Habitat creation Manipulation of disturbance regimes (e.g. fuel reduction and fire suppression to prevent forest conversion) Conservation call options	Assign 0-3 points. Consider number of qualifying actions, their efficacy, and any other relevant factors

Table 2c. Description of resilience promotion score assignment

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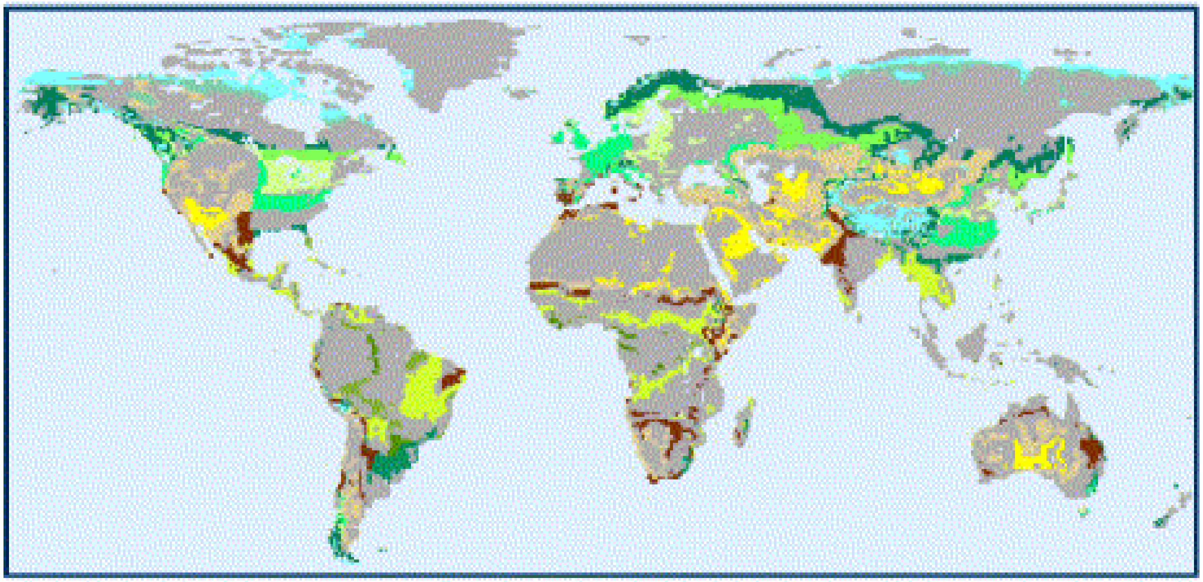
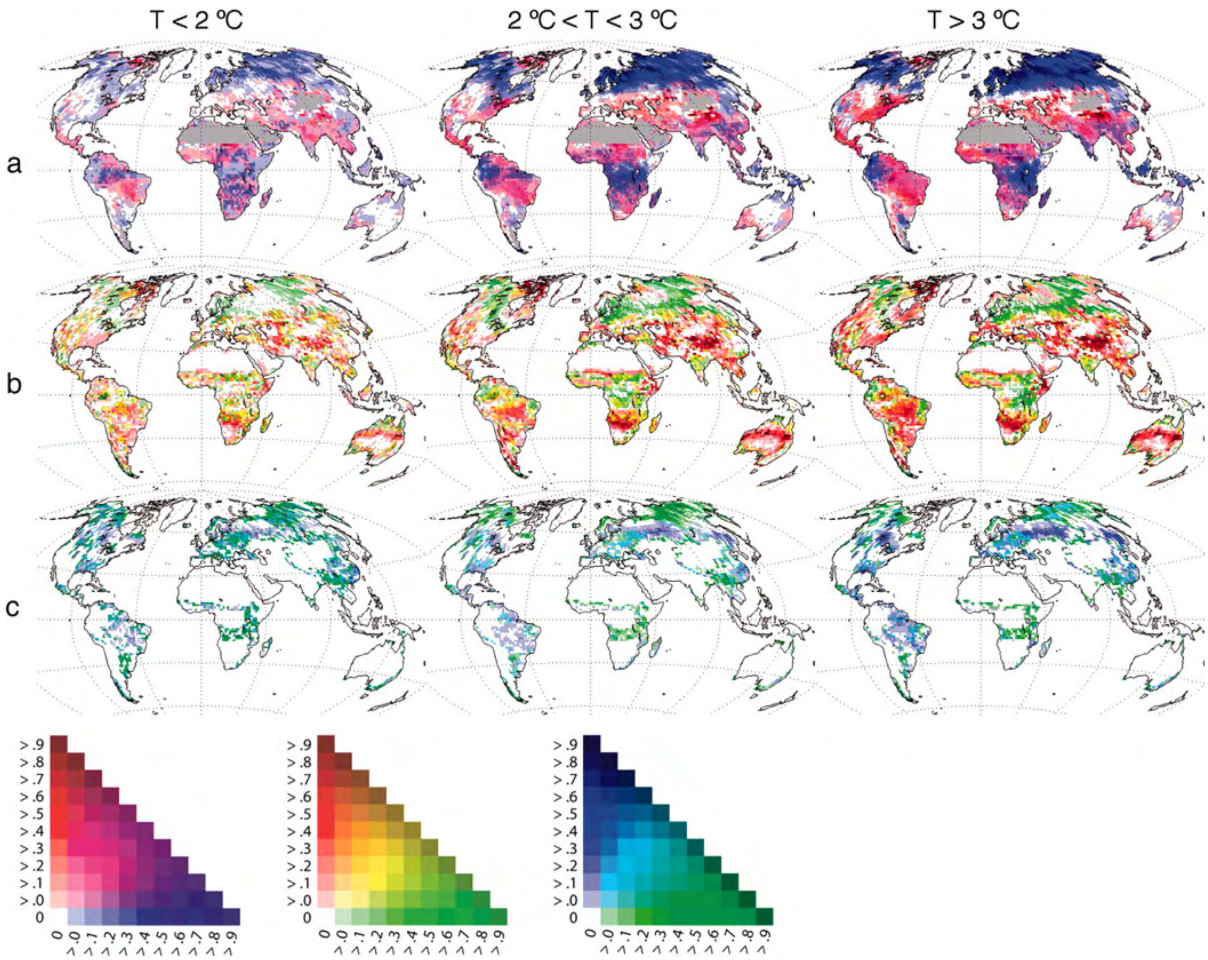
Appendix A – Global change maps from studies in Table 1

Figure A1 Biome changes from Leemans & Eickhout



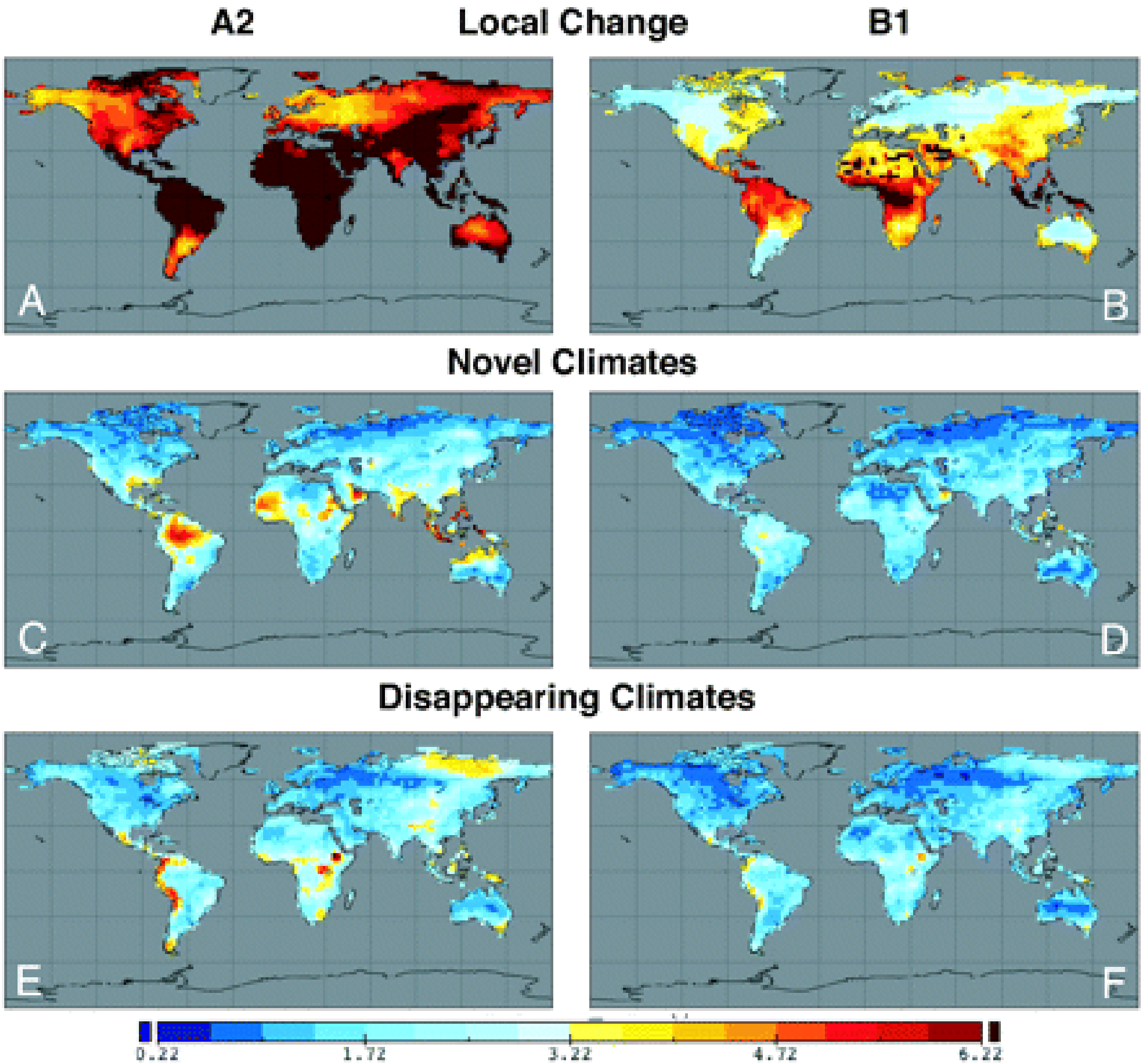
Leemans & Eickhout (2004) Fig. 1. Ecosystem shifts for mean global temperature increase of 3 °C. Colors reflect ecosystem types impacted. Types of forest are green, grasslands are brown, deserts are yellow, ice is blue. Note that the colors are not well-reproduced so eastern Amazon, central Africa, and southeast Asia actually represent tropical forests.

Figure A2



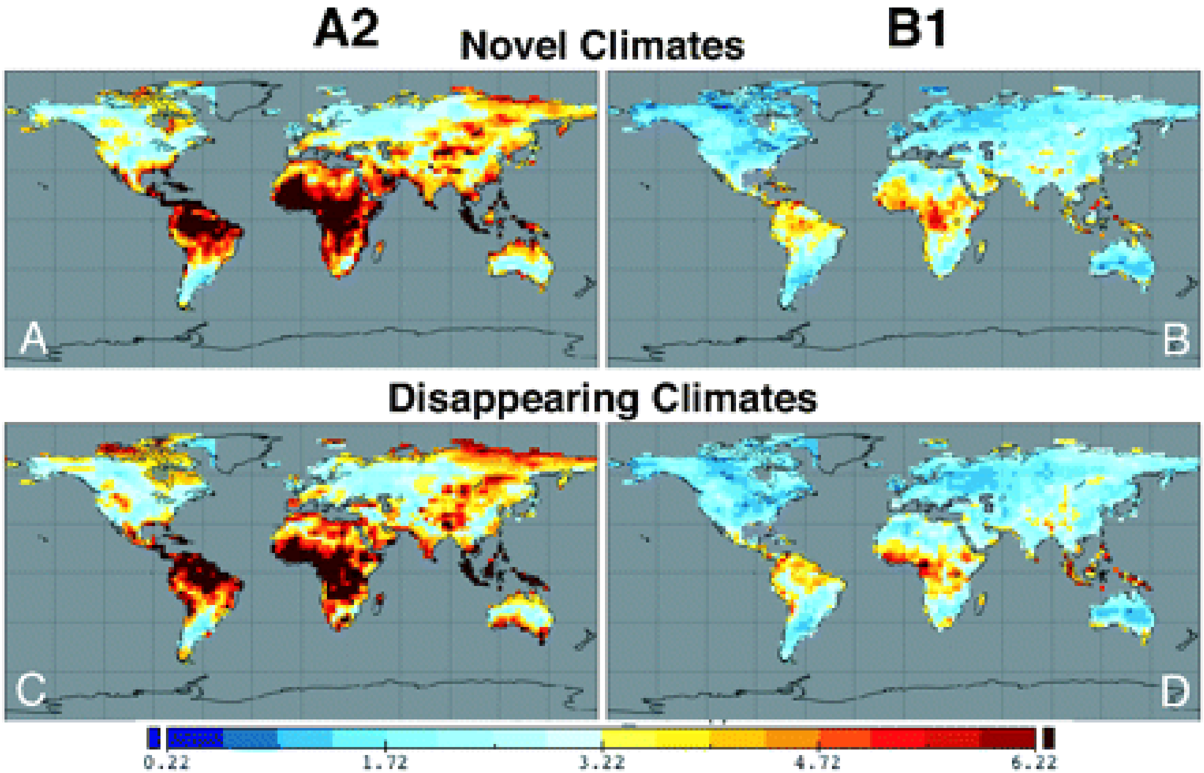
Scholze et al. (2006) Fig. 2. Probability of exceeding critical levels of change by 2071-2100. a) runoff (blue increase, red decrease) b) wildfire frequency (red increase, green decrease) c) biome change (blue forest to non-forest, green is loss of forest). GCM ensembles with several scenarios grouped according to predicted level of warming.

Figure A3



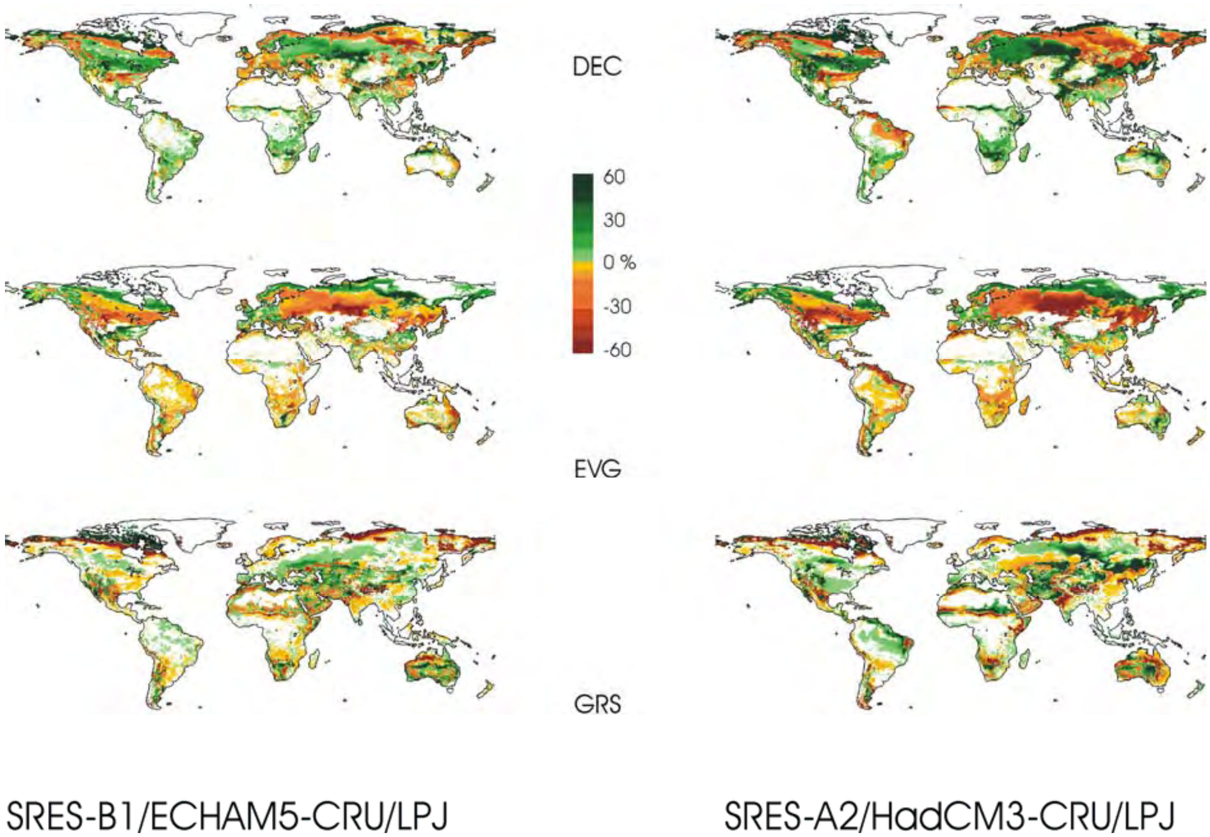
Williams et al (2007). Fig2. A & B depict the multidimensional climate distance (essentially summer and winter temperature and summer and winter precipitation) between current and future climates at the grid cell. C & D depict the minimum distance between future climate at the grid cell and current climate considering all grid cells. E & F depict the minimum distance between current climate at the grid cell and future climate considering all grid cells. GCM ensemble, scenario A2 on left, B1 on right.

Figure A4



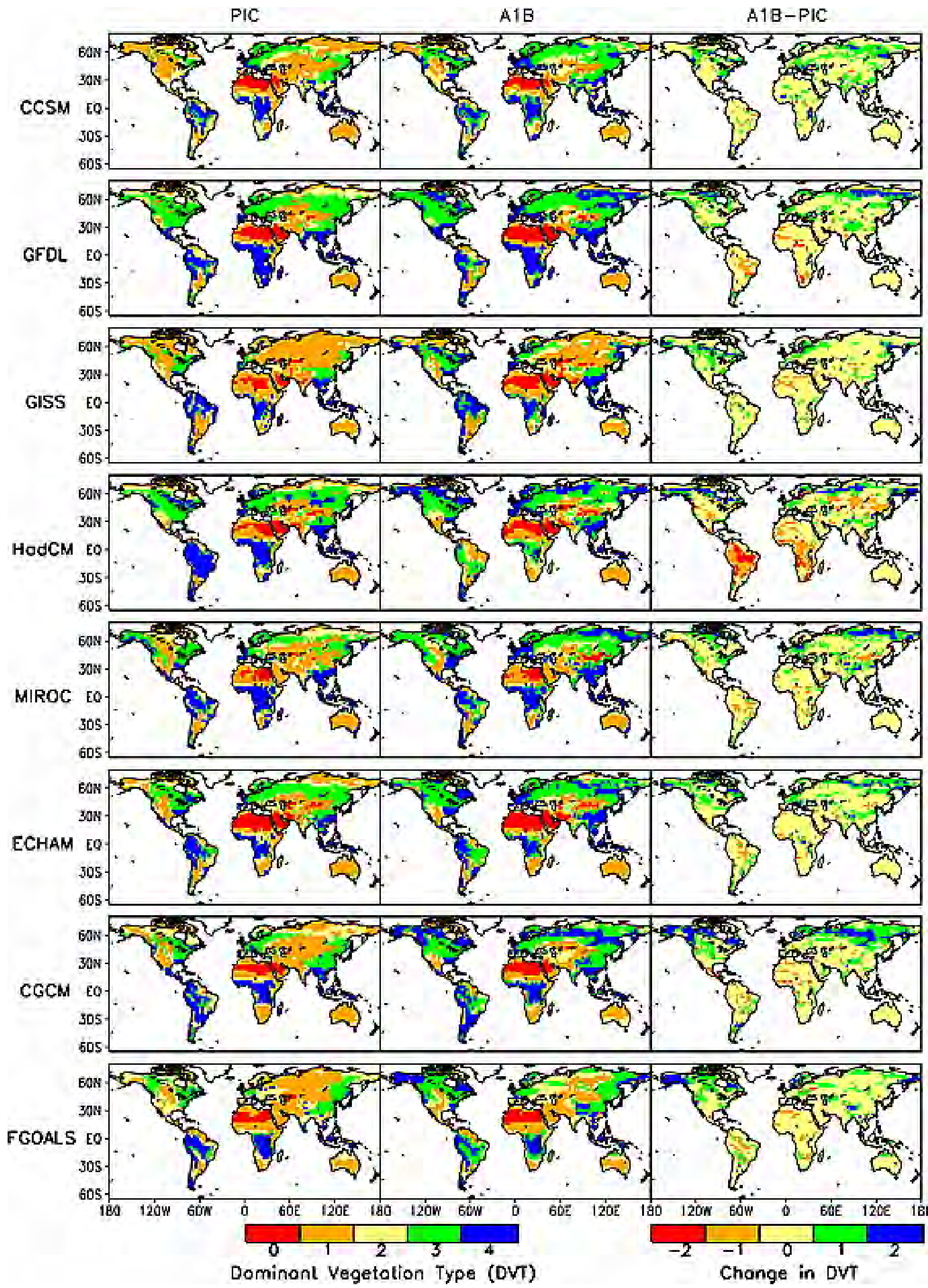
Williams et al (2007). Fig3. A & B depict the minimum multidimensional climate distance (essentially summer and winter temperature and summer and winter precipitation) between future climate at the grid cell and current climate considering cells with 500km for focal cell. C & D depict the minimum distance between current climate at the grid cell and future climate considering grid cells within 500km of focal cell. GCM ensemble, scenario A2 on left, B1 on right.

Figure A5



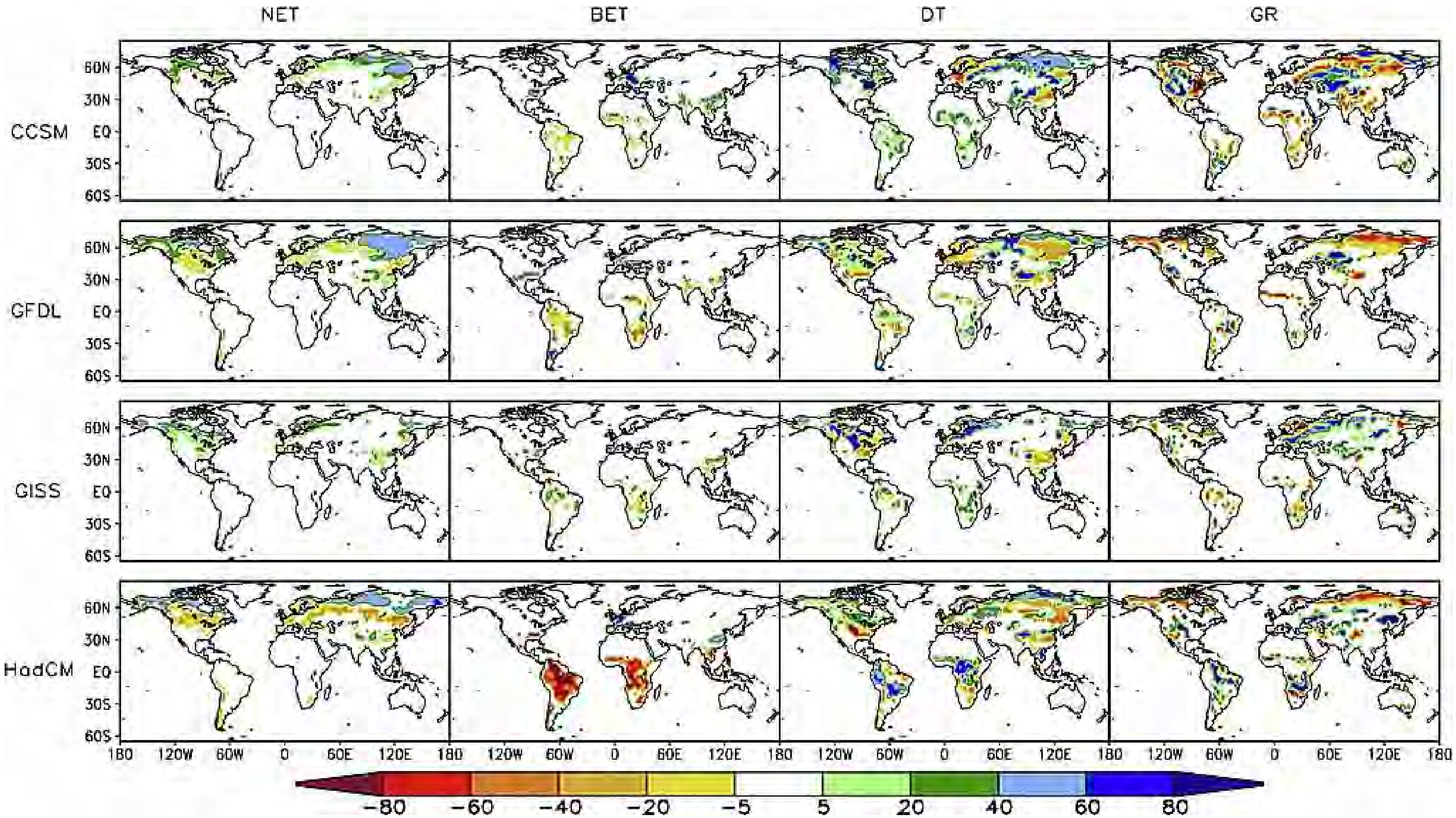
Lucht et al. (2006) Fig 1. Changes in cover of different types of vegetation functional types. Top panel is deciduous woody vegetation, middle panel is evergreen woody vegetation, lower panel is grasses. Low change (ECHAM5 GCM under B1 scenario) is on left; high change (HadCMR GCM under A2 scenario) is on right.

Figure A6



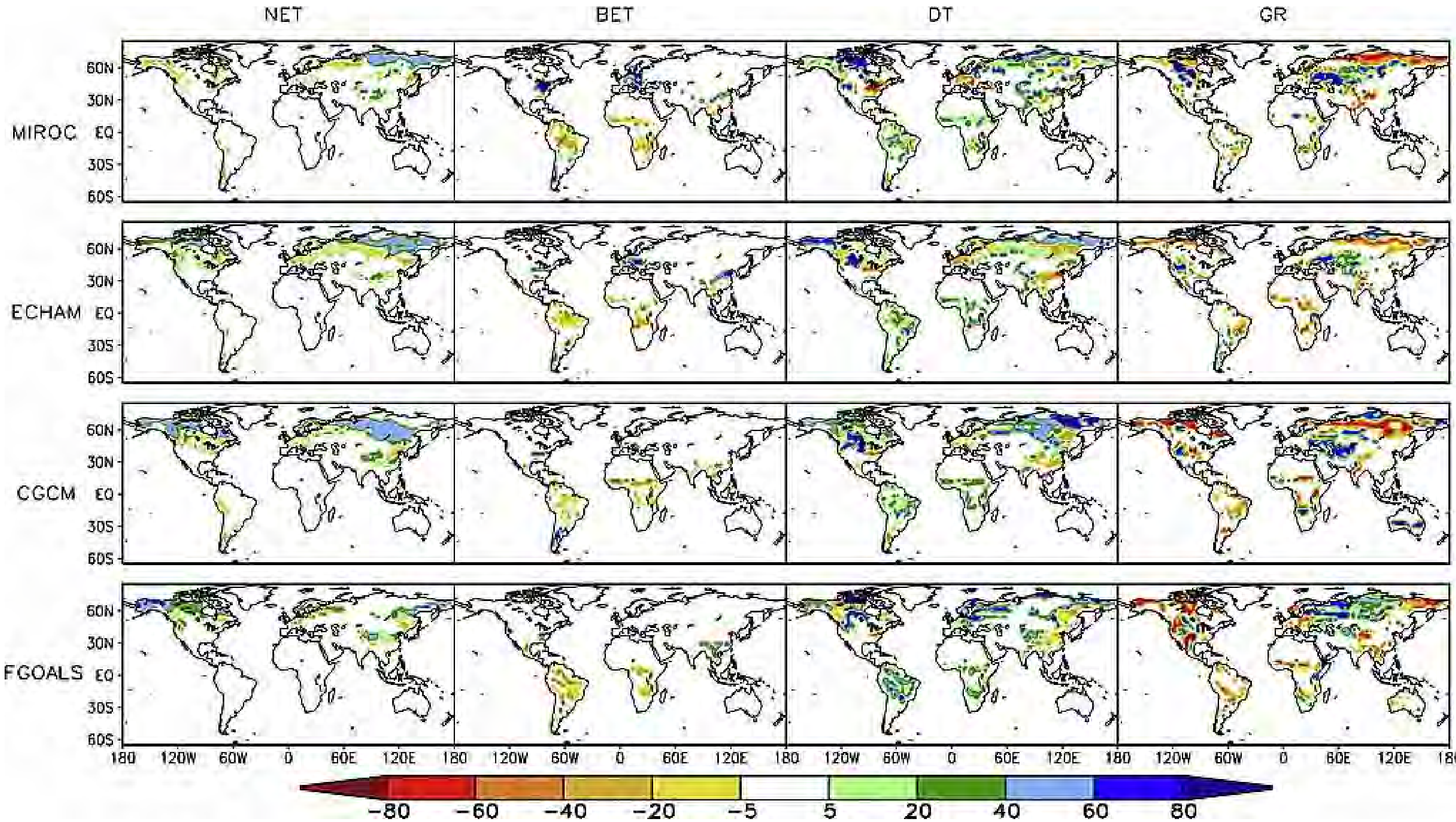
Alo & Wang (2008) Figure 2. Dominant vegetation for different GCMs. The left panel represents the pre-industrial control scenario, the middle panel represents the A1B scenario and the right panel is the change between the two. In the left and middle panels, red is desert, orange is grass with fractional coverage of less than 40%, yellow is grass with fractional coverage greater than 40%, green is deciduous trees, and blue is evergreen trees. In the right panel, red represents a 2-grade degradation of vegetation (towards desert), orange is a 1-grade degradation, yellow is no change, green is a 1-grade enhancement (towards evergreen trees), and blue is a 2-grade enhancement.

Figure A7



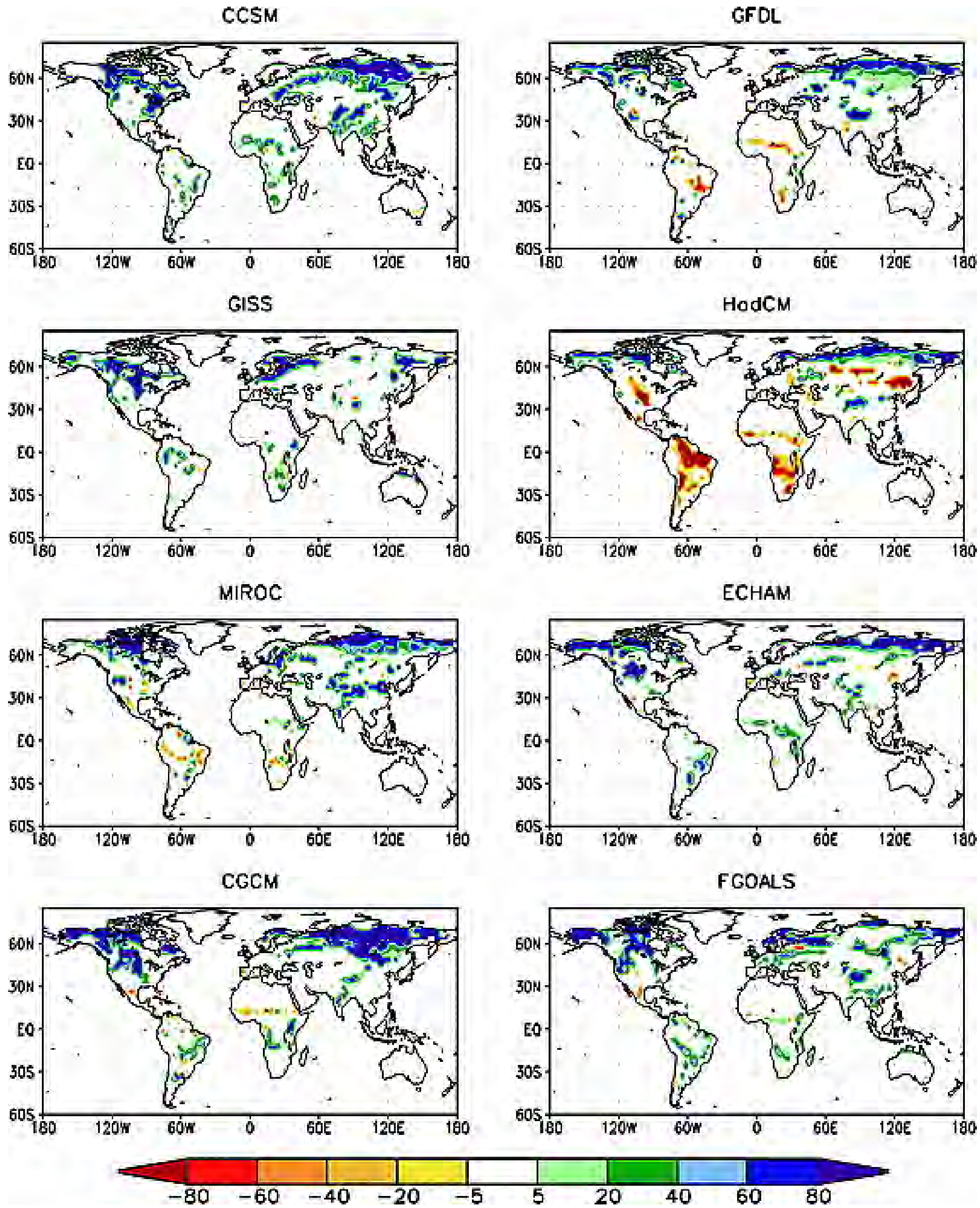
Alo & Wang (2008) Figure 3a. Geographic distribution of changes in the fractional coverage (between pre-industrial control and A1B scenarios), as a percentage of vegetated portion of grid cell for four categories of plant functional types: needleleaf evergreen trees (NET), broadleaf evergreen trees (BET), deciduous trees (DT), and grasses (GR). Results are for four GCMs.

Figure A8



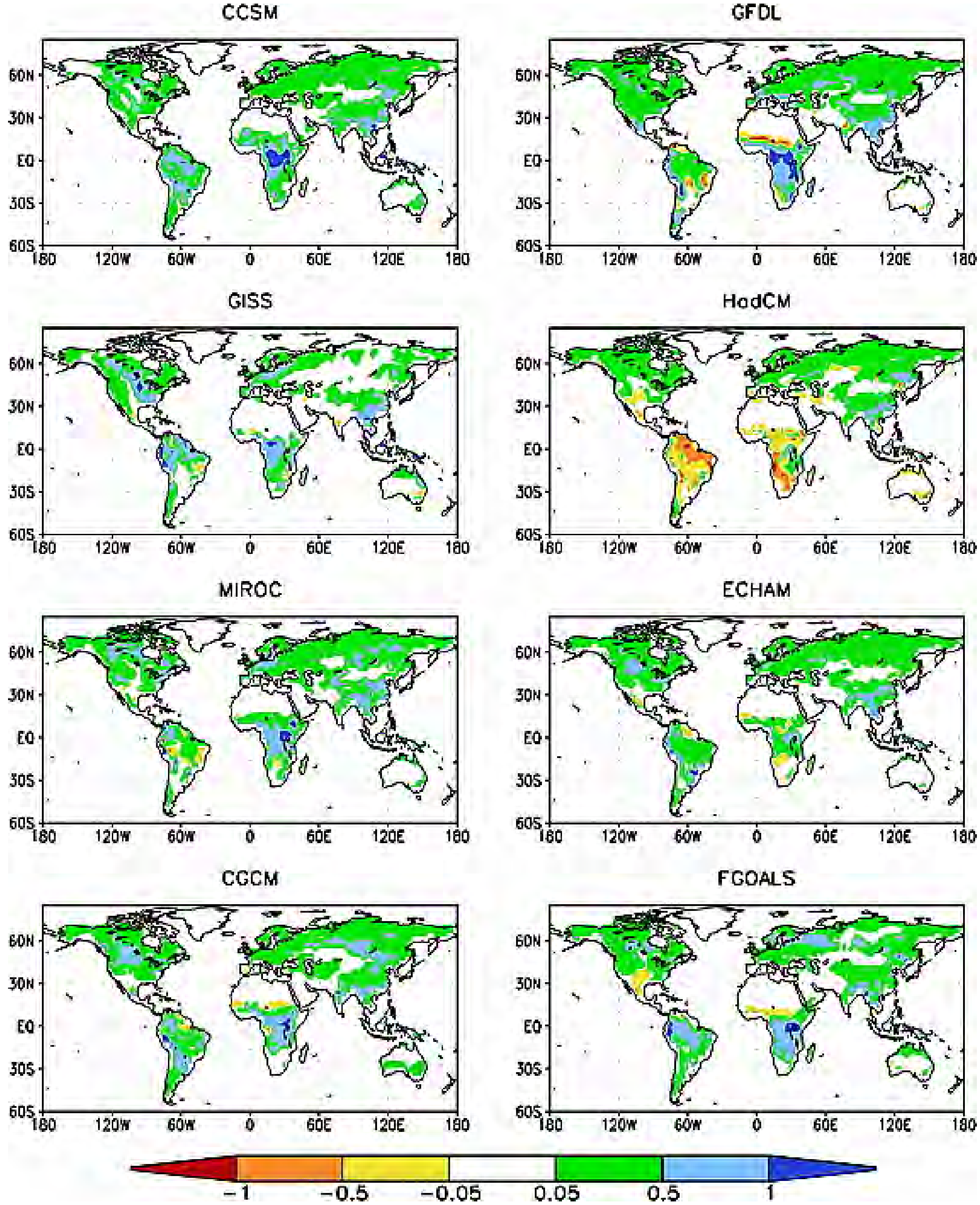
Alo & Wang (2008) Figure 3b. Same as previous figure for a different set of four GCMs.

Figure A9



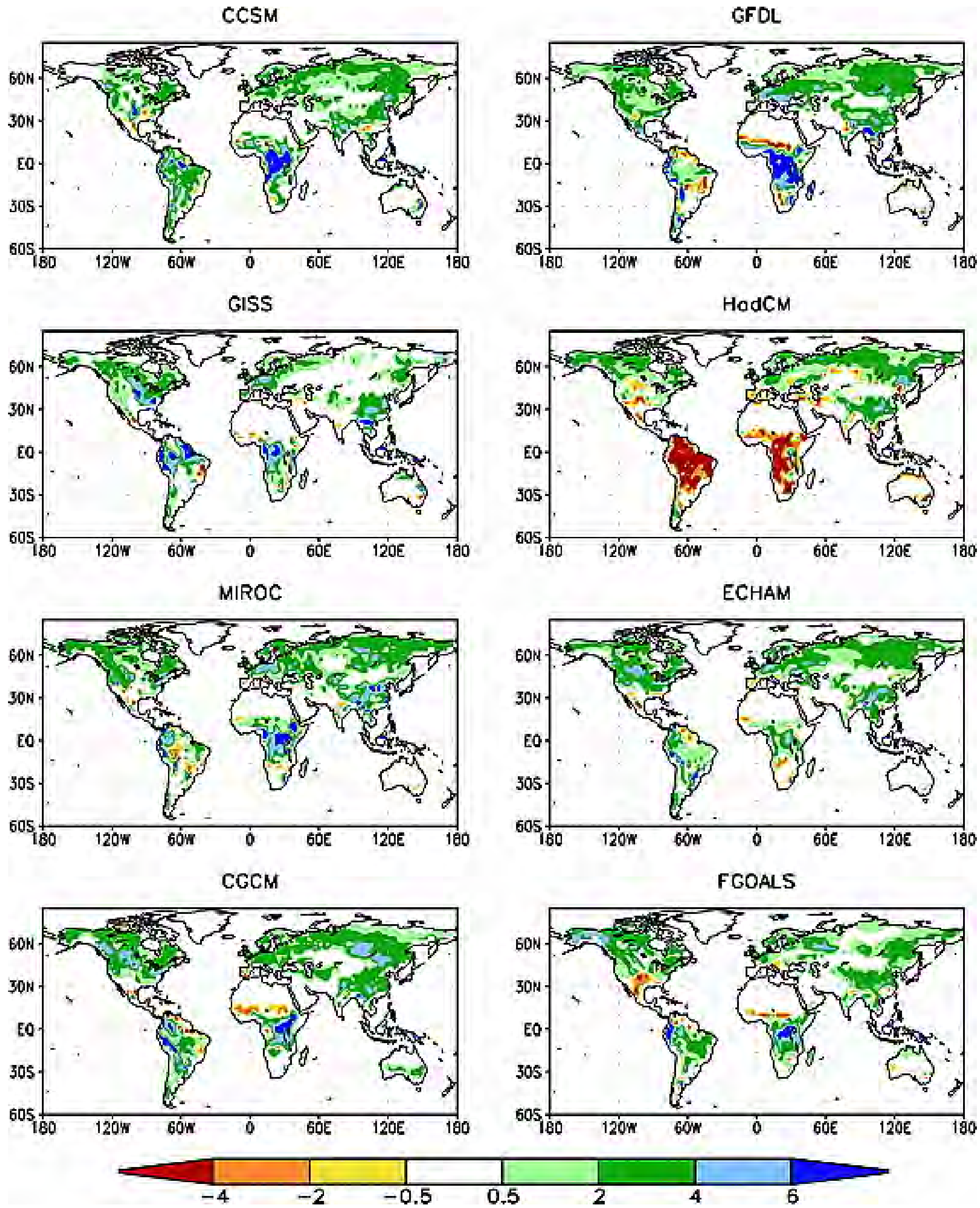
Alo & Wang (2008) Figure 4. Geographic distribution of changes in the fractional coverage (between pre-industrial control and A1B scenarios), as a percentage of vegetated portion of grid cell, of forest (all woody plant functional types) for eight GCMs,

Figure A10



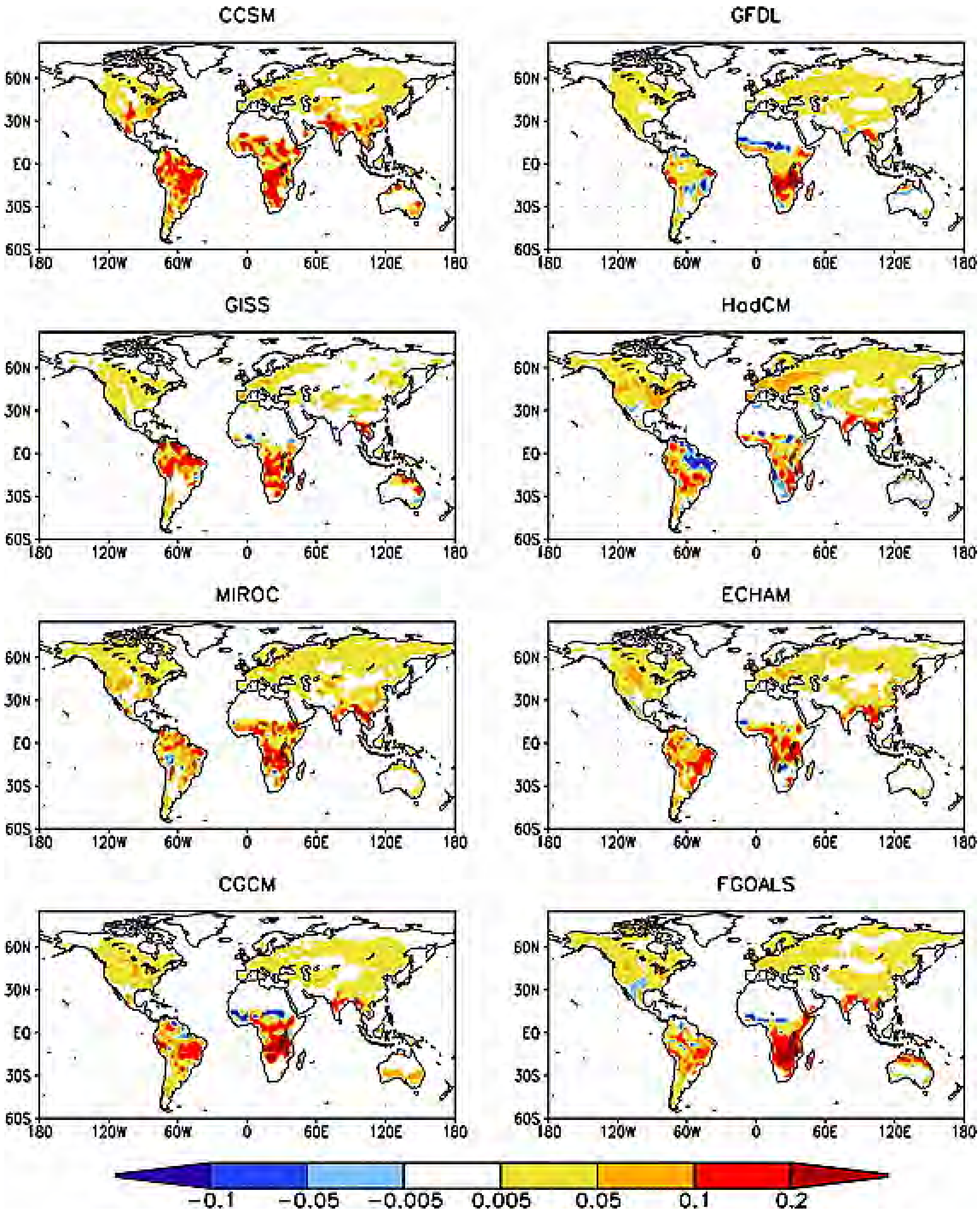
Alo & Wang (2008) Figure 5. Simulated changes (between pre-industrial control and A1B scenarios) in Net Primary Productivity (NPP) (in kg C/m2 of vegetated portion of grid cell) for eight GCMs.

Figure A11



Alo & Wang (2008) Figure 6. Simulated changes (between pre-industrial control and A1B scenarios) in Leaf Area Index (LAI) (in m2/m2) for eight GCMs,

Figure A12



Alo & Wang (2008) Figure 7. Simulated changes (between pre-industrial control and A1B scenarios) in carbon flux to atmosphere due to fire (in kg C/m2 of vegetated portion of grid cell) for eight GCMs

Appendix B – Draft list† of species vulnerability traits

Trait category	Detailed traits
Range characteristics	**1. Range size**
	1.1. Extent of occurrence (or distribution polygon area)
	1.2. Area of occupancy
	1.3. (Maps and spatial characteristics of mapped range)
	2. Use of space
	2.1. Altitude
	2.5. What is the species' vertical niche in its habitat?
	2.6. Fragmentation metric and shape of range
	3. Habitat
	3.1. Habitat type
	4. Microhabitat
	4.1. Specialised habitat/microhabitat
	4.2. Physiologically buffered from climate change impact by microhabitat
	5. Home range size
	5.1. Home range size
Population	**1. Population size**
	1.2. Number of individuals
	1.3. Population fluctuations
	1.4. Vulnerable to allee effects
	2. Density
	2.1. Population density within AOO
	3. Metapopulation dynamics
	3.2. Size of largest viable subpopulation
	3.3. Area needed to sustain a minimum viable population
	3.4. Connection between subpopulations
Life history	**1. Reproductive rate**
	1.2. Mean age of first reproduction
	1.3. Longevity* (incl. seed longevity)
	Mean survival
	1.4. Reproductive rate; clutch/lietter size
	2. Life history stages
	2.1. Number of life history stages

	2.2. No. life stages with different habitat/microhabitat requirements
	3. Resilience
	3.1. Naturalized outside native range or successfully translocated
	3.4. At which stage of succession would this species establish?
	3.5. Persists in anthropogenic habitats
Breeding system	**1. Reproductive strategy**
	1.1. Mode of reproduction
	1.2. Does reproduction happen in a single event per lifetime (semelparously) or on multiple occasions (iteroparously)?
	Primary mating system
	1.4. Self incompatible
	1.6. Parental care
	1.7. Are individuals bisexual/hermaphroditic?
	1.10. Pollination or fertilisation vector
	2. Sex ratio
	2.1. Proportion of females
	2.2. Environmental determination
	2.3. Skewed reproductive success (i.e. some members of one sex prevent others from reproducing)
Behavioural characteristics	**1. Activity timing**
	1.1. Time of activity
	1.2. Seasonal estivation, hibernation, torpor or dormancy?
	2. Congregatory behaviour*
	Migratory behaviour
	2.1. Does the species need to congregate for reproduction or foraging?
	3. Social structure
Multi species interactions	**1. Trophic level**
	1.1. Trophic position
	2. Energy acquisition*
	Diet
	3. Dependency on other species*
	3.1. Approximately how many other species is this species dependent on for survival (including hosts, prey & mutualisms)?

	3.2. Is the species dependent on an interspecific interaction that is likely to be disrupted by climate change (including indirectly for example via CO_2 fertilisation)?
Vagility	**1. Dispersal vector**
	1.1. Does the species disperse actively (vs. passively) e.g. through flight or migration?
	1.2. If passively dispersed, what is the dispersal vector?
	2. Intrinsic dispersal capacity
	2.1. Mean intrinsic dispersal distance
	2.1. Max dispersal distance in short to medium term
	3. Barriers to dispersal
	3.1. Capability of dispersing to a new range [needs further guidance to be useful]
	3.2. Opportunity to disperse limited by geographical barriers
	3.3. Is the opportunity to disperse limited by anthropogenic barriers
Physiological characteristics	**1. Environmental tolerances**
	1.1. Is there a known environmental tolerance that is likely to be exceeded due to climate change?
	1.2. Defining environmental tolerances:
	1.2.1. What is the species' temperature; rainfall, pollution etc. range? (min; max; optimum)
	2. Photosynthetic physiology
	2.1. What type of photosynthesis does the plant use? (C3, C4, CAM, don't know; facultative vs. obligate)
	3. Body size
	3.1. Adult male size
	3.2. Adult female size
	3.3. Seed size
	4. Growth from
	4.1. Growth form
Phenology	1. **Phenological cues***
	1.1. Is the species' persistence dependent on a specific environmental trigger that's likely to be disrupted by climate change (at any stage in the species' life history)?

Genetic characteristics	**1. Genetic diversity**
	1.1. Is the taxon known to have gone through a genetic bottle neck in the past or be known to have low genetic diversity?
	1.2. Genetic diversity (value)

† Adapted from Foden & Collen (2007). Provided via personal communication from Wendy Foden (February 19, 2008). Do not cite.