Impacts of Climate Change on Terrestrial Ecosystems and Adaptation Measures for Natural Resource Management

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Abstract Emissions from motor vehicles, power plants, deforestation, and other human sources are warming the Earth and damaging ecosystems and human well-being. Field observations from around the world have detected significant changes in terrestrial ecosystems and attributed them to climate change rather than other factors. Climate change has shifted the ranges of plants, animals, and biomes, altered the timing of life events such as plant flowering and animal migration, increased wildfires, and driven 75 frog and other amphibian species to extinction. Projections of future climate change and analyses of vulnerability indicate that unless we substantially reduce greenhouse gas emissions, further warming may overwhelm the adaptive capacity of many species and ecosystems. Climate change could convert extensive land areas from one biome to another, alter global biogeochemical cycles, and isolate or drive numerous species to extinction. Natural resource managers are developing adaptation measures to help species and ecosystems cope with the impacts of climate change.

Keywords Adaptation · Climate change · Ecological impacts · Natural resource management · Vegetation shifts

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Introduction

Emissions from motor vehicles, power plants, deforestation, and other human sources are warming the Earth and damaging ecosystems and human well-being. Climate change increased global average surface temperature 0.7 ± 0.2ºC from 1906 to 2005 (IPCC, 2007a). Field observations show that this warming has shifted the geographic ranges of plants, animals, and biomes (major vegetation formations) around the world (IPCC, 2007b; Rosenzweig et al., 2008; Gonzalez et al., 2010). Climate change has also altered the phenology (timing of life events such as plant flowering and animal migration) of numerous species on all continents (IPCC, 2007b; Rosenzweig et al., 2008). Climate change has lifted the cloud deck in Costa Rica cloud forest, driving 75 frog and other amphibian species to extinction (Pounds et al., 2006).

Projections of future climate change using general circulation models, dynamic global vegetation models, and climate envelope models indicate that unless we substantially reduce greenhouse gas emissions, increased temperatures and other changes in climate could exceed the resilience of many ecosystems (IPCC, 2007b). Climate change could convert extensive land areas from one biome to another, increase wildfire, and isolate or drive to extinction numerous plant and animal species. Approximately 20–30% of species assessed so far are at high risk of extinction if global mean temperatures increase 2–3°C above preindustrial levels (Thomas et al., 2004; IPCC, 2007b). Greenhouse gas emissions and modified evaporation and runoff due to deforestation and forest degradation could substantially change global

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biogeochemical cycles. All of these ecological impacts of climate change threaten to reduce ecosystem services, including the provision of erosion control, firewood, flood control, food, forest carbon sequestration, freshwater, medicine, timber, and other necessities for survival (Millennium Ecosystem Assessment, 2006).

The world can avoid the worst impacts of climate change by improving energy efficiency, expanding

Table 1 Major observed and projected impacts of climate change on terrestrial ecosystems and potential adaptation measures

	Observed impacts in the twentieth century with global increase of 0.7ºC	Projected impacts in the twenty-first century with global increase of 2–4ºC	Adaptation measures
Biomes	Biome shifts toward polar or equatorial regions and upslope, in Africa, Europe, and North America (Gonzalez, 2001; Peñuelas and Boada, 2003; Beckage et al., 2008; Kullman and Öberg, 2009, Gonzalez et al., 2010)	Biome shifts toward polar or equatorial regions and upslope across extensive areas (IPCC, 2007b; Sitch et al., 2008; Gonzalez et al., 2010)	Managing for habitat type, management of climate change refugia
Species ranges	Range shifts in the direction expected with climate change for 80% of 434 plant and animal species from around the world (Parmesan and Yohe, 2003)	Range disappearance for 15–37% of plant and animal species examined from around the world (Thomas et al., 2004)	Protection of climate change refugia, habitat corridors
Phenology	Earlier flowering, leafing, and migration for 62% of 677 plant and animal species from around the world (Parmesan and Yohe, 2003)	Continued changes in flowering, leafing, and animal migration (IPCC, 2007b)	Food propagation for mistimed migrants
Species extinctions	Extinction of 75 frog and other amphibian species in Costa Rica (Pounds et al., 2006), significant declines in Antarctic penguins (Emslie et al., 1998; Fraser et al., 1992; Barbraud and Weimerskirch, 2001; Wilson et al., 2001)	High risk of extinction for 20–30% of assessed species from around the world (Thomas et al., 2004; IPCC, 2007b)	Managed relocation
Wildfire	Fire frequency increase of 400% in western United States (Westerling et al., 2006), increase of burned forest area in Canada (Gillett et al., 2004)	High fire forest dieback risk for half of the area of the Amazon (Golding and Betts, 2008), increased fire in boreal forest (Balshi et al., 2009)	Prescribed burning
Pests	Extensive forest dieback from bark beetles in western North America (Breshears et al., 2005; Raffa et al., 2008)	Continued bark beetle infestations in western North America (Kurz et al., 2008)	Prescribed burning
Global biogeochemistry	Increase in global net primary productivity from CO_2 fertilization and longer growing seasons (Nemani et al., 2003), decrease in tropical forest biomass in Costa Rica from increased respiration at night (Clark et al., 2003)	Enhanced vegetation growth slows, then reverses by the end of the twenty-first century, so that the terrestrial biosphere converts from a carbon sink to a carbon source (IPCC, 2007a)	Natural regeneration and enrichment planting of adapted plant species

public transit, installing wind, solar, and other renewable energy systems, conserving forests, and using other currently available measures to reduce greenhouse gas emissions (Pacala and Socolow, 2004; IPCC, 2007c). Nevertheless, a lag between emissions to the atmosphere and warming of the land and oceans commits the world to another 0.3–0.9ºC of warming from 2000 to 2100, due to cumulative emissions since the beginning of the Industrial Revolution (Wigley, 2005; IPCC, 2007a). Consequently, human communities and ecosystems will need to adapt to a certain amount of warming. Natural resource managers are developing adaptation measures to help species and ecosystems cope with the impacts of climate change (IPCC, 2007b; US CCSP, 2008).

This chapter discusses the impacts of climate change on terrestrial ecosystems and adaptation measures for natural resource management. Terrestrial ecosystems include tundra, forests, woodlands, grasslands, and deserts. Other chapters in the book cover agricultural, coastal, freshwater, marine, and wetland ecosystems. This chapter first presents information on ecological impacts that field observations have already detected and attributed to twentieth century climate change. It then presents projections of potential impacts of continued climate change in the twenty-first century. The sections on observed and projected impacts each examine three broad areas: vegetation, fauna, and global biogeochemical cycles of carbon and water. Finally, the chapter presents adaptation solutions that could help species and ecosystems cope with climate change. Table 1 summarizes the major impacts and adaptation options. This chapter depends especially on the findings of the Intergovernmental Panel on Climate Change (IPCC).

Observed Impacts

Observed Changes in Climate

Human activities have raised carbon dioxide (CO_2), the principal greenhouse gas, to its highest level in the atmosphere in 800,000 years (Lüthi et al., 2008). Analyses reveal that the added gas bears the unique chemical signature of burned coal and oil and not the sign of gases from volcanoes or geysers (IPCC, 2007a). The accumulation of greenhouse gases has raised global temperatures to their warmest levels in 1,300–1,700 years (Mann et al., 2008). Orbital cycles and other natural factors account for only 7% of observed warming (IPCC, 2007a).

In 2008, motor vehicles, power plants, and other fossil fuel-burning industrial sources emitted greenhouse gases to the atmosphere at a rate (mean ± 66% confidence interval) of 8.7 ± 0.5 Gt C/y and deforestation contributed emissions of 1.2 ± 0.75 Gt C/y, while global vegetation and soils removed greenhouse gases from the atmosphere at a rate of 4.7 ± 1.2 Gt C/y (IPCC, 2007a; Le Quéré et al., 2009). While the biosphere is currently a net carbon sink, human activities emit twice the amount of greenhouse gases than vegetation, soils, and the oceans can naturally absorb. That is the fundamental imbalance that causes climate change.

Climate change warmed global temperatures 0.7 ± 0.2ºC from 1906 to 2005 (IPCC, 2007a). Temperatures in the Arctic have been warming at almost twice the rate of the rest of the world (ACIA, 2004; IPCC, 2007a). Winter temperatures in some parts of the temperate zone have warmed almost as quickly as annual temperatures in polar areas (USGCRP, 2009).

In the twentieth century, climate change reduced Northern Hemisphere snow cover 7% and accelerated the melting of glaciers around the world to its greatest rate in 5,000 years (IPCC, 2007a). From 1890 to 1986, warm temperatures melted 160 m of ice thickness from Tasman Glacier, New Zealand (Kirkbride, 1995). In the western United States, more precipitation has been falling as rain than as snow since 1949 (Knowles et al., 2006). Climate change is increasing the proportion of Atlantic hurricanes in the most intense categories (Mann et al., 2009).

Climate change has increased the intensity and length of droughts since 1970, especially in subtropical and tropical areas (IPCC, 2007a). Warmer ocean temperatures and the reduction of continental vegetation cover significantly reduced rainfall in the African Sahel during the nineteenth and twentieth centuries in the most severe drought in the instrumental record in the world (Zeng et al., 1999; Giannini et al., 2003; Dai et al., 2004).

Observed Impacts on Vegetation

Field observations demonstrate that climate change has altered the distribution and condition of vegetation around the world. Warmer temperatures and changing patterns of precipitation have shifted the geographic range of plants and biomes, altered plant phenology, increased wildfire, and exacerbated pest outbreaks (IPCC, 2001b; IPCC, 2007b). Climate change affects ecosystems at the same time as other potential stresses, including acid rain, agricultural expansion, air and water pollution, dams, deforestation, desertification, increased livestock herding, invasive species, ozone, urbanization, and water withdrawals. Although ecosystems are not static, climate change and these other stresses are pushing some ecosystems out of historic ranges of variability.

Determination of impacts of climate change on ecosystems involves two distinct research procedures: detection and attribution. Detection is measurement of historical changes that are statistically significantly different from natural variability (IPCC, 2001a). Attribution is determination of the relative importance of different factors in causing observed change. If statistical analysis and multiple lines of evidence demonstrate that observed changes are (1) unlikely to be due entirely to natural variability, (2) consistent with estimated or modeled responses, and (3) inconsistent with alternative plausible explanations, then the analysis and evidence can reasonably attribute the cause of the observed change to climate change (IPCC, 2001a). Attribution of ecological impacts to the human activities that cause climate change requires a two-step 'joint attribution': attribute ecological changes to changes in climate factors, then attribute changes in climate factors to human emissions of greenhouse gases (IPCC, 2007b; Rosenzweig et al., 2008).

Building on IPCC (2001b, 2007b) detection of numerous ecological changes and their attribution to human-caused climate change, Rosenzweig et al. (2008) assembled over 29,500 time series of statistically significant temperature-related changes detected in physical and ecological systems and statistically attributed over 90% of those changes to observed human-caused increases in temperature. The database of observed changes included any published statistically significant trend in a physical or ecological system related to temperature, occurring between 1970 and 2004 and documented with at least 20 years of data. Over 28,000 of the cases examined terrestrial ecosystems.

Biomes are the major vegetation formations of the world, including tundra, forests, woodlands, grasslands, and desert. Spatial patterns of temperature and precipitation determine the global distribution of biomes. When climate change exceeds plant physiological thresholds, alters mortality and recruitment, and modifies wildfire and other disturbances, it can shift the location of biomes latitudinally (toward polar and equatorial regions) and elevationally (up mountain slopes).

Observed changes in temperature or precipitation that fall one-half to two standard deviations outside of historical mean values have caused biome changes in the twentieth century (Gonzalez, 2001; Peñuelas and Boada, 2003; Beckage et al., 2008; Kullman and Öberg, 2009, Gonzalez et al., 2010). In Africa, climate change and desertification have caused a long-term decline in rainfall that has caused extensive forest dieback (Fig. 1) and shifted the Sahel (savanna), Sudan (woodland), and Guinea (tropical forest) ecological

Fig. 1 Yir (*Prosopis africana*) tree that died in Senegal as part of a vegetation shift in the African Sahel driven by a rainfall decline caused by climate change (Gonzalez, 2001). Photo by P. Gonzalez

zones 25–30 km toward the Equator from 1945 to 1993 (Gonzalez, 2001). In Spain, temperate broadleaf forest has shifted upslope into montane heathland (Peñuelas and Boada, 2003). In the northeast United States, temperate broadleaf forest has shifted upslope to replace boreal conifer forest (Beckage et al., 2008). In Scandinavia, boreal conifer forest has shifted upslope to replace alpine grassland (Kullman and Öberg, 2009).

Field observations have detected range shifts of many individual plant species. Of 434 plant and animal species examined with distribution data spanning at least 20 years, Parmesan and Yohe (2003) found that 80% shifted in the direction expected with climate change. For the 99 Northern Hemisphere plant and animal species with suitable range data, Parmesan and Yohe (2003) calculated average shifts of 6.1 km per decade northward or 6.1 m per decade upslope. Examining over 1,400 plant and animal species with suitable distribution data spanning at least 10 years, Root et al. (2003) found that 80% have shifted in the direction expected with climate change. For 171 forest plant species in France, Lenoir et al. (2008) found that the average optimum elevation (elevation with maximum probability of finding a species) shifted upslope by 29 m per decade between the periods 1905–1985 and 1986–2005. Numerous cases of drought-induced forest dieback around the world demonstrate that climate change has increased tree mortality in many ecosystems (Allen et al., 2010).

Plant species and biomes also shifted extensively across the globe during the 11,000–21,000 years from the Last Glacial Maximum to the present (Overpeck et al., 2003). Tree lines shifted 1,000 km away from the poles during those long millennia (ACIA, 2004). In contrast, climate change in the late twentieth century has shifted some plant ranges by that same magnitude in less than a century (NAS, 2008).

Phenology is the timing of life events, including, for plants, leaf unfolding, spring flowering, fruit ripening, leaf coloring, and leaf fall. Climate change has altered the phenology of numerous plant species (Parmesan and Yohe, 2003; Root et al., 2003; IPCC, 2007b). Meta-analysis of published research on 677 plant and animal species examined with data spanning at least 20 years found 62% of the species exhibited spring advance (Parmesan and Yohe, 2003).

In 21 European countries, climate change advanced flowering times earlier in the spring for 78% of 542 plant species from 1971 to 2000 (Menzel et al., 2006). In England, climate change has advanced spring flowering for 385 plant species (Fitter and Fitter, 2002). In the eastern United States, climate change advanced the date of spring flowering of 100 tree and forb species by an average of 2.4 days from 1970 to 1999 (Abu-Asab et al., 2001). Examination of the longest series of direct phenology observations in the world, the records of cherry (*Prunus* spp.) blossoming in Japan, shows no clear trend from 1400 to 1900, but significant advance after 1952 (Menzel and Dose, 2005). Records of tree leaf unfolding in England since 1736 show an average advance of 2.5 ± 1.7 days/century for oaks (*Quercus* spp.; Thompson and Clark, 2008). Analysis of 172 plant and animal species showed an average advance of spring phenology events of 2.3 days per decade, primarily in the twentieth century (Parmesan and Yohe, 2003).

Fire forms a natural component of forest and grassland ecosystems (Bowman et al., 2009). Many plant species depend on fire to initiate germination, remove competing plant species, or control insects and pathogens. Fire-dependent vegetation covers much of the world, especially in the tropics and subtropics. Climate change is altering key factors that control fire: temperature, precipitation, humidity, wind, biomass, vegetation species composition and structure, and soil moisture. Consequently, wildfire frequency and extent has increased in some ecosystems. In mid-elevation conifer forests of the western United States, an increase in spring and summer temperatures of 1ºC from 1970 to 2003, earlier snowmelt, and longer summers increased fire frequency 400% and burned area 650% (Westerling et al., 2006). An increase of burned area in forests across Canada from 1920 to 1999 is consistent with climate change and not natural variability (Gillett et al., 2004). Across North American boreal forest, total burned area increased by a factor of 2.5 from 1959 to 1999, whereas burned area of human-ignited fires remained constant (Kasischke and Turetsky, 2006).

Climate warming is changing the abundance and range of pests and pathogens (IPCC, 2007b). In the United States, climate change extended the range of at least two species of damaging bark beetles from 1960 to 1994 (Williams and Liebhold, 2002). An epidemic of mountain pine beetle and spruce bark beetle now spreads across western North America, damaging conifer tree species across at least 47,000 km^2 (Raffa et al., 2008). Intense drought and beetle damage have caused massive dieback of pinyon pine (*Pinus edulis*) across the southwest United States (Breshears et al., 2005).

Observed Impacts on Fauna

Climate change has lifted the cloud deck in the Monteverde cloud forest, Costa Rica, causing a fungus infection that has driven the golden toad (*Bufo periglenes*) and 74 other amphibian species to extinction (Pounds et al., 2006). These comprise the only documented species extinctions to date caused by climate change. Climate change has also driven other amphibian population declines in Latin America and the Caribbean (Alexander and Eischeid, 2001; Ron et al., 2003; Burrowes et al., 2004).

Polar bears (*Ursus maritimus*) inhabit sea ice over the continental shelves and inter-island archipelagos of the Arctic, depending for food on seals that breed on the ice. On Hudson Bay, Canada, break-up of sea ice advanced three weeks from the 1970s to the 1990s, driving polar bears ashore earlier with reduced fat reserves and causing them to fast for longer periods of time (Stirling et al., 1999). Preliminary estimates indicate that the western Hudson Bay population has declined from 1,200 bears in 1987 to 950 bears in 2004 (Stirling et al., 1999).

Melting of Antarctic sea ice has caused significant population declines of Adélie penguins (*Pygoscelis adeliae*) and emperor penguins (*Aptenodytes forsteri*) because they depend on sea ice to feed on marine species (Emslie et al., 1998; Fraser et al., 1992; Wilson et al., 2001). At Terre Adélie (66ºS), emperor penguin populations declined 50% from 1952 to 2000 (Barbraud and Weimerskirch, 2001). On Anvers Island (64–65ºS), Adélie penguin populations have declined 70% (Emslie et al., 1998; Fraser et al., 1992), although populations are thriving further south at Ross Island (77ºS), an effective poleward range shift (Wilson et al., 2001).

Climate change has shifted the range of many types of animals (IPCC, 2007b). Field observations document upslope range shifts of 16 butterfly species in Spain (Wilson et al., 2005), 37 dragonfly and damselfly species in Great Britain (Hickling et al., 2005), the white stork (*Ciconia ciconia*) in Poland (Tryjanowski et al., 2005), and the grey-headed flying fox (*Pteropus poliocephalus*) in Australia (Tidemann et al., 1999). From 1914 to 2006, half of 28 small mammal species monitored in Yosemite National Park, USA, shifted upslope an average of ~500 m, consistent with an observed 3°C increase in minimum temperatures (Moritz et al., 2008). From 1900 to 1998, two-thirds of 35 nonmigratory butterfly species examined in Europe shifted their range north, while only two species ranges shifted south (Parmesan et al., 1999).

As described in the previous section, meta-analyses of time series of at least 10 or 20 years have demonstrated twentieth century changes in the phenology of numerous plant and animal species. Animal life events that are occurring earlier include emergence from hibernation, amphibian calling and mating, spring bird migration, egg-laying, and appearance of butterflies (Parmesan and Yohe, 2003; Root et al., 2003; Rosenzweig et al., 2008). Short-range bird migration has advanced for nine bird species in Australia (Green and Pickering, 2002), 36 bird species in Sweden (Stervander et al., 2005), and 52 bird species in the eastern United States (Butler, 2003). In the Rocky Mountains, USA, emergence of yellow-bellied marmots (*Marmota flaviventris*) from hibernation advanced 23 days from 1975 to 1999, consistent with a local temperature increase of 1.4ºC (Inouye et al., 2000). During the same period, snowmelt and plant flowering did not change, generating a possible phenology mismatch between marmots and their food plants.

Observed Impacts on Global Biogeochemistry

Biogeochemical cycles are the circulation of carbon, water, and other chemical compounds essential to life through the atmosphere, oceans, land, vegetation, and animals of the Earth. Satellite data, field sampling, and computer modeling indicate that climate change is particularly altering the global carbon and water cycles (IPCC, 2001a; IPCC, 2007a). This section describes some of the major connections between observed impacts of climate change on terrestrial ecosystems and global biogeochemical cycles.

Increased atmospheric CO_2 concentrations can enhance vegetation growth though the 'CO_2 fertilization' effect. CO_2 fertilization and lengthening

Fig. 2 Tropical rainforest at La Selva Biological Station, Costa Rica, viewed from the carbon flux tower that furnished data to help detect a decrease in forest biomass caused by climate change (Clark et al., 2003). Photo by P. Gonzalez

of the growing season together may be increasing global carbon sequestration by vegetation. Analysis of the satellite-derived Normalized Difference Vegetation Index (NDVI); (Tucker, 1979) showed a 6% increase in global net primary productivity (NPP) from 1982 to 1999, with substantial increases in tropical ecosystems (Nemani et al., 2003). A review of observations from various forest ecosystems also suggest global increases in forest productivity (Boisvenue and Running, 2006). In the Amazon, CO_2 fertilization and faster forest turnover rates may be causing an increase in the density of lianas (Phillips et al., 2002). On the other hand, warmer night temperatures reduced forest biomass in Costa Rica tropical rainforest (Fig. 2) from 1984 to 2000, due to increased respiration at night (Clark et al., 2003).

In a self-reinforcing cycle, climate change is increasing wildfire in some forest ecosystems (Gillett et al., 2004; Westerling et al., 2006), releasing more CO_2, which causes climate change. Wildfire currently emits 2–4 Pg C/y, up to half the amount of greenhouse gases of fossil fuel burning (Schultz et al., 2008; Bowman et al., 2009). Of the 2–4 Pg C/y of wildfire emissions, burning to deforest land may account for 0.6 Pg C/y (Bowman et al., 2009).

The increase in the proportion of Atlantic hurricanes in the most intense categories due to climate change (Mann et al., 2009) may also be increasing physical disturbance of forest ecosystems, windthrow, and carbon emissions from dead trees. One storm, Hurricane Katrina, felled trees containing ~0.1 Pg C (Chambers et al., 2007).

Due to increased inputs of heat energy into the atmosphere, land, and oceans, climate change is increasing convection and precipitation globally (IPCC, 2007a). In a self-reinforcing cycle, increased precipitation contributes to increased growth in forest ecosystems, increasing evapotranspiration inputs that contribute to cloud formation and precipitation. On the other hand, warmer temperatures in some ecosystems may be reducing soil moisture, increasing evapotranspiration, and decreasing moisture available for plant growth (NAS, 2008).

Projected Impacts

Projected Changes in Climate and Uncertainties

Climate change is a function of two sets of factors: greenhouse gas emissions and the complex responses of the atmosphere, land, and oceans. Consequently, projections of future climate depend on emissions scenarios (derived from trends in population, resource use per person, and emissions per unit of resource use) and general circulation models (GCMs; computer simulations of the atmosphere, land, and oceans). The relatively straightforward physics of the greenhouse effect governs global temperatures. In contrast, changes in precipitation, cloudiness, cyclones, the El Niño-Southern Oscillation, and other climate phenomena depend on more complex processes.

IPCC has developed a standard set of six emissions scenarios, ranging from a high-energy efficiency future to continuation of business-as-usual, on which research groups in 10 countries have run 23 GCMs (IPCC, 2007a). Uncertainties in projections of future climate change derive mainly from the range in emissions estimates from the scenarios and accuracy differences among the GCMs.

IPCC projects global average temperature increases of 1.8–4ºC between the periods 1980–1999 and 2090–2099 for the six scenarios (IPCC, 2007a). Analyses of potential mitigating effects of emissions reductions policies project warming of 0.8–7.8°C with no emissions reductions and 0.5–4.4°C with a range of emissions reduction policies (Van Vuuren et al., 2008). Actual greenhouse gas emissions through 2004 have exceeded the highest IPCC emissions scenario, suggesting warming in the upper part of the range of projections (Raupach et al., 2007).

Global average temperatures in the Last Glacial Maximum were approximately 4–7°C cooler than present (IPCC, 2007a; NAS, 2008). The warming after the ice ages occurred over 10–20 millennia, in contrast to projections of future warming of a similar magnitude in just one century.

GCMs project an increase in global average precipitation. Boreal and polar areas may receive large increases while subtropical areas may experience decreases in rainfall (IPCC, 2007a). Most projections indicate more frequent extremes in temperature and precipitation, leading to more frequent droughts and flooding.

Projected Impacts on Vegetation

The magnitude of projected climate changes would render ecosystems vulnerable to biome shifts, phenology changes, wildfire increases, species extinctions, and other impacts. Assessment of potential impacts requires analysis of the vulnerability of ecosystems. Vulnerability to climate change is the degree to which a system is susceptible to, and unable to cope with, adverse effects (IPCC, 2007b). Vulnerability is a function of three components: exposure, sensitivity, and adaptive capacity. Exposure consists of the climate that a species or ecosystem experiences. Sensitivity is the degree to which a species or ecosystem changes due to climate change. Adaptive capacity is the ability of a species or ecosystem to adjust, moderate potential damage, take advantage of new conditions, or cope with warming and other impacts (IPCC, 2007b).

Climate projections provide information on exposure. To assess sensitivity and adaptive capacity, dynamic global vegetation models (DGVMs) (Daly et al., 2000; Sitch et al., 2008) simulate the spatial distribution of vegetation, biomass, and wildfire based on climate, soil, and observed characteristics of plant functional types. Climate envelope, bioclimatic, or niche models simulate the geographic range of individual species based on areas that seem to fall within the climate tolerance of a plant or animal (Elith et al., 2006). Uncertainties in DGVMs and climate envelope models arise from incomplete information on relationships of organisms to climate parameters, dispersal capabilities, inter-specific interactions, and evolutionary adaptations.

Vulnerability analyses indicate that projected climate change, combined with deforestation, pollution, and other stresses, could overwhelm the adaptive capacity of many species and ecosystems by 2100 (IPCC, 2007b). Climate change and other stresses may elicit threshold-type responses, in which species or ecosystems experience sudden changes at threshold levels where pressures overwhelm adaptive capacities (Burkett et al., 2005). Some potential changes, such as species extinctions, will be irreversible.

Spatial analyses of observed twentieth century climate change and projected twenty-first century vegetation indicates that one-tenth to one-half of global land may be highly (confidence ~0.80) to very highly (confidence ~0.95) vulnerable to vegetation shifts (Gonzalez et al., 2010). DGVMs project extensive latitudinal and elevational biome shifts (Fig. 3) around the world (IPCC, 2007b; Sitch et al., 2008; Gonzalez et al., 2010). The most vulnerable biomes may be alpine grassland, tundra, and boreal forest, replaced in many areas by temperate conifer forest, boreal forest, and temperate conifer forest, respectively. Conditions favorable to alpine ecosystems may completely disappear from the tops of mountains.

Increased drought and fire threaten to cause extensive dieback of Amazon rainforest. High fire risks are projected for half of the area of the Amazon (Golding and Betts, 2008). A global mean temperature rise >2ºC could convert 20–90% of Amazon tropical evergreen broadleaf forest to grassland (Jones et al., 2009).

Projected global increases in drought due to climate change (Burke et al., 2006) threaten to exacerbate desertification and cause biome changes in

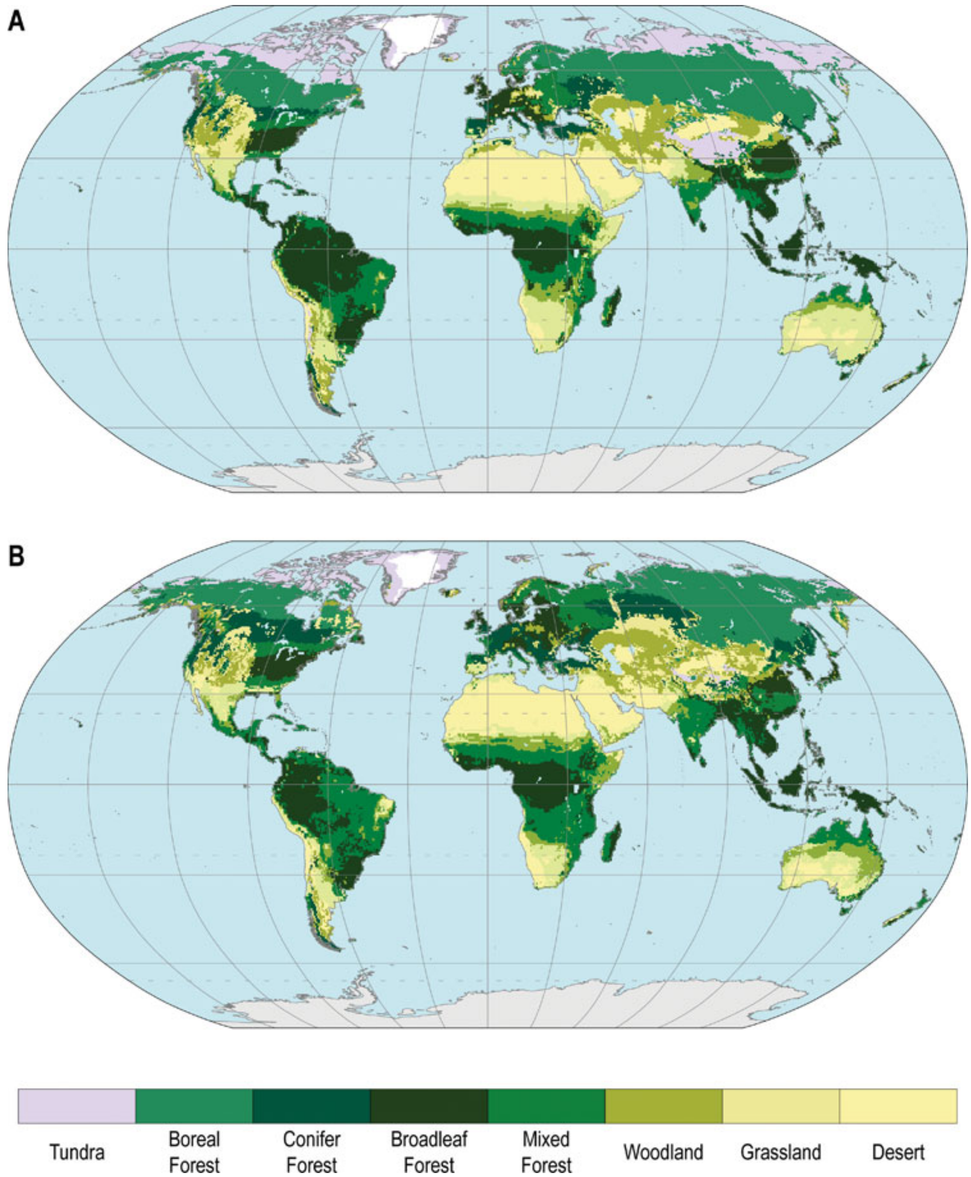

Fig. 3 Projected biome changes shown by modeling of global vegetation under (**a**) observed climate in the period 1961–1990 and (**b**) projected climate in the period 2071–2100, showing the worst case of nine combinations of three IPCC (2007a) emissions scenarios and three general circulation models, with global average temperature increases of 2.4–4.0ºC (Gonzalez et al., 2010)

the African Sahel and other arid, semi-arid, and dry subhumid areas (IPCC, 2001b). Drought in Southern Africa could decrease vegetation cover in the Kalahari enough to remobilize sand dunes (Thomas and Leason, 2005).

Climate change may also shift geographic ranges of numerous individual plant species (IPCC, 2007b). Contracting patches of habitat, dispersal limitations, and novel climates that species have never before encountered (Williams et al., 2007) may overwhelm the adaptive capacities of some species. Climate envelope modeling of the ranges of 1,103 plant and animal species under projected warming 2–3ºC above preindustrial temperatures indicate that climate change places 15–37% of examined species at risk of extinction (Thomas et al., 2004).

Climate change threatens the unique flora of South Africa and Namibia, characterized by high numbers of endemic species with restricted ranges. Warming of 1.5–2.7°C above pre-industrial temperatures could contract the area of the Succulent Karoo biome by 80% and push 2,800 plant species to extinction (Hannah et al., 2002; Midgley et al., 2002). Warming of 2.7°C above pre-industrial temperatures could contract the area of the Cape Fynbos biome by 65%, driving 23% of the species to extinction (Thomas et al., 2004). Warmer temperatures and decreased rainfall under mid-range climate projections could place 5% of the 159 endemic plant species of Namibia at risk of extinction and render half of the species vulnerable to substantial range contractions (Thuiller et al., 2006).

Although warming of the world after the Last Glacial Maximum triggered extensive biome shifts and extinctions (NAS, 2008), the slow pace of climate change allowed surviving species to move and reassemble into functional ecosystems as the ice retreated (Pitelka et al., 1997; Overpeck et al., 2003). The rapid pace of current climate change may prevent such an orderly reconfiguration.

In addition to range shifts, climate change may increase fire frequencies around the world (IPCC, 2007b; Golding and Betts, 2008; Balshi et al., 2009), although fire may decrease in areas of higher precipitation. Many projected impacts of climate change, including warmer temperatures, decreased precipitation, increased storm activity, and increased fuels from dying vegetation, contribute to increased fire.

Projected Impacts on Fauna

Climate envelope modeling, as discussed in the previous section, indicates that climate change places 15–37% of examined plant and animal species at risk of extinction (Thomas et al., 2004). The species most at risk are limited-range endemics and alpine and polar species. Unique characteristics of polar animals render them more vulnerable to climate change. Many polar animal species depend on habitats with extensive snow and ice. Polar ecosystems are relatively simple, with low densities of predators and competitors. In the Arctic, most animals have evolved fewer traits for competition, predator avoidance, and resistance to pathogens not found in cold regions (ACIA, 2004). Due to their high mobility, the dominant response of many arctic animals to climate change may be relocation rather than adaptation (ACIA, 2004).

Polar bears face a high risk of extinction with warming of 2.8°C above preindustrial temperatures (ACIA, 2004). Climate change also threatens to reduce populations of emperor penguins (*A. forsteri*) (Barbraud and Weimerskirch, 2001) and other Antarctic bird species (Croxall et al., 2002).

Climate envelope models project substantial vulnerability of species in temperate and tropical ecosystems. In Mexico, a warming of 2.3ºC above preindustrial temperatures could commit 2–20% of mammals, 3–8% of birds, and 3–15% of butterflies to extinction (Peterson et al., 2002). In Kruger National Park, South Africa, a 2.3ºC warming could commit 24–59% of mammals, 28–40% of birds, 13–70% of butterflies, and 1–45% of reptiles to extinction (Erasmus et al., 2002). Also in South Africa, a warming of 4ºC could reduce the range of the Mountain Wheat-ear bird (*Oenanthe monticola*) by half (Simmons et al., 2004). In Queensland, Australia, warming > 4ºC could cause the extinction of all endemic rainforest species, including 57 frog and mammal species (Williams et al., 2003).

Climate change can also increase the vulnerability of animal species dependent on streams and rivers fed by mountain snowpack, which climate change is reducing. As described in the section "Observed Impacts on Fauna", changes in phenology could initiate mistiming between animal behavior and food plant development and between predator and prey activity.

Projected Impacts on Global Biogeochemistry

Projected impacts of climate change on terrestrial ecosystems could substantially alter global biogeochemical cycles. Experimental enrichment of four forest sites to the CO_2 concentrations that would accompany a 3°C warming above preindustrial temperatures increased NPP 23 ± 2% (Norby et al., 2005). At higher CO_2 concentrations, plants would not need to open their stomata as much, which, in other experiments, yielded plant water savings of 5–15% (Wullschleger and Norby, 2001; Cech et al., 2003). Projections indicate that the combination of CO_2 fertilization, improved water use efficiency, and the expansion of global forest area due to biome shifts will continue to increase global NPP and total sequestration of carbon in vegetation through much of the twenty-first century (IPC, 2007a; Sitch et al., 2008).

Yet, saturation of CO_2 fertilization by mid-century, nitrogen and phosphorus limitations to plant growth, heat stress on plants, increased soil respiration, increased fire and other disturbances, and methane emissions from melting of tundra and permafrost may convert terrestrial ecosystems into a net emitter of greenhouse gases by 2100 (IPCC, 2007a). Continued tropical deforestation would add even more emissions.

In polar and boreal areas, the replacement of snow-covered ground by boreal conifer forest with dark foliage can reduce albedo (reflectance) and increase local temperature (Bala et al., 2007). This local warming, in addition to forest decline at the southern edge of boreal forest and potential increases in wildfire, may offset cooling effects of increased carbon sequestration in the new boreal forest areas (ACIA, 2004; IPCC, 2007a).

Projected increases in wildfire (Sitch et al., 2008; Balshi et al., 2009) may create a positive feedback for climate warming through significant emissions of greenhouse gases that would further increase temperatures (Randerson et al., 2006). In another possible positive feedback cycle, climate change may exacerbate outbreaks of bark beetles, causing extensive forest dieback, increasing greenhouse gas emissions, and further increasing global temperatures (Kurz et al., 2008).

In addition to increasing greenhouse gas emissions to the atmosphere, forest dieback and degradation could substantially alter segments of the hydrologic cycle (IPCC, 2007a). Forest dieback in the Amazon and other tropical rainforests could reduce precipitation regionally. Projected reductions of vegetation cover in many areas could increase runoff, decrease soil moisture, and decrease precipitation in affected areas. Decreased precipitation could create positive feedback cycles in affected areas by further reducing vegetation cover and increasing greenhouse gas emissions.

Adaptation

Types of Adaptation

Adaptation is an adjustment in natural or human systems in response to climate change, to moderate harm or exploit new conditions (IPCC, 2007b). Adaptation to climate change falls into three broad types. First, natural selection of individual plants and animals with resilient characteristics will, as these individuals pass their genes to offspring, drive the evolution of species more adapted to changed climate conditions. Second, natural resource management agencies and individual people can adjust land and water management practices at specific sites to help individual plant and animal species cope with climate change. Third, natural resource management agencies and other organizations can adjust management plans across broad landscapes to facilitate adaptation of species and ecosystems. In the first type of adaptation, plant and animal species are adapting. In the second and third types, agencies and people are adapting.

Evolutionary Species Adaptation

Observations indicate that some species are evolving to adapt to climate change. In Europe, the blackcap warbler (*Sylvia atricapilla*) evolved so that the direction of its migration route extends its winter range northward (Berthold et al., 2003). In England, the speckled wood butterfly (*Pararge aegeria*) has evolved in a way that dispersal morphology and life history traits have allowed the species to expand its geographic range (Hill et al., 1999; Hughes et al., 2003). The North American red squirrel (*Tamiasciurus hudsonicus*) has also evolved so breeding occurs slightly earlier as climate change advances the beginning of spring (Berteaux et al., 2004).

Species-Specific Natural Resource Management Adaptation

This section provides examples of adaptation measures in which natural resource agencies and individual people adjust land and water management practices at specific sites to help individual plant and animal species cope with climate change. Scott et al. (2008) describe some of these examples.

Prescribed burning is the planned ignition of fire to simulate the natural effects of fire in an ecosystem adapted to fire. Fire forms a natural component of forest and grassland ecosystems. In areas projected to experience an increase in fire frequency due to climate change, the preemptive use of fire can reduce the amount of litter and woody debris that might cause catastrophic stand-replacement fires and damage tree species adapted to less intense fire regimes. Although prescribed burning may release greenhouse gases in the short term, it can create conditions favorable for the growth of large trees, increasing carbon sequestration in the long term.

Natural regeneration and enrichment planting of adapted plant species starts with identification of native species that already grow in an area and that possess characteristics adapted to projected climate conditions. Natural regeneration would involve protection of existing small trees of the species of interest to increase their survival. Enrichment planting would involve planting new seedlings where the existing density of the species is sparse. High genetic diversity of species at the low elevation edge of their range may require special protection of those areas to conserve and propagate their seeds (Hampe and Petit, 2005).

Food propagation for mistimed migrants would involve the planting of food plants in situations where climate change has decoupled the phenology of animals and their food plants. This may be necessary, for example, with migratory birds that arrive earlier in the spring at breeding grounds where food plants are not developing earlier.

Riparian reforestation of native riparian tree species along river and stream banks could provide shade to keep water temperatures from warming excessively during summer months. This could create thermal refugia for fish and other species.

Managed relocation is an intervention technique that involves the intentional movement of populations or species from current areas of occupancy to locations where the probability of future persistence is projected to be higher (Richardson et al., 2009). It may become necessary in extreme cases where climate change threatens to strand limited-range endemic species, polar species, or alpine species on mountain peaks or other locations where warming may eventually eliminate all suitable habitat. The release of species that could become invasive in the areas of relocation presents a challenge to this adaptation measure.

Monitoring species abundance and distributions in permanent ecological plots will provide essential data to track the effectiveness of adaptation measures.

Landscape-Scale Natural Resource Management Adaptation

Biome shifts and other impacts of climate change threaten to reduce the effectiveness of the existing network of national parks, forests, reserves, and other natural resource management areas because managers generally designed those networks without considering the dynamics of climate change. This section provides examples of adaptation measures at the landscape scale, in which natural resource management agencies and other organizations adjust landscape management plans to facilitate adaptation of species and ecosystems. Generally, landscape adaptation measures concern the structured configuration of a network of existing natural resource areas combined with the targeted acquisition of new areas. Scott et al. (2008) describe some of these examples.

Analysis of vulnerability of geographic areas to climate change would involve spatial analyses to categorize areas within a landscape into three classes: areas of high, medium, or low vulnerability (Gonzalez et al., 2010). Analyses would require spatial data on exposure (climate projections), sensitivity (ecological models), and adaptive capacity (field data). The results would guide prioritization of geographic areas and planning of management actions (Hannah et al., 2002). In British Columbia, Canada, one proposed adaptation system classifies forest areas based on four combinations of exposure (low or high) and adaptive capacity (low or high) and assigns natural regeneration, mixed-species planting, enrichment planting, fire fuel reduction, and strict protection measures based on the classification (Nitschke and Innes, 2008). A global analysis of observed climate and projected vegetation identifies vulnerable areas and potential refugia around the world (Gonzalez et al., 2010).

In existing management areas, prioritization of places of higher vulnerability for adaptation measures would channel resources to those areas that may require more intensive management. Potentially greater disturbances and species turnover in vulnerable areas would require costly adaptation measures such as prescribed burning and invasive species removal. Areas of unique ecological or cultural value would continue to merit high priority.

Acquisition of new areas in climate change refugia would take advantage of less demanding management needs of those areas. Climate change refugia are locations more resistant to climate change due to wide climate tolerances of individual species, the presence of resilient assemblages of species, and local topographic and environmental factors. Because of the lower probability of drastic change, refugia will likely require less intense management interventions to maintain viable habitat and cost less than management of vulnerable areas (Griffith et al., 2009). Acquisition of new areas should continue to adhere to the principles of representation, the protection of examples of different ecosystem types practiced, for example, by Parks Canada, and replication, the protection of several separate areas of the same type of habitat to provide insurance of loss of any single replicate (US CCSP, 2008).

Establishment and maintenance of corridors will facilitate species dispersal and migration as climate change shifts the location of habitats over time. Fragmentation of habitat will impair the ability of species to adapt to climate change (IPCC, 2007b). Because fundamental ecosystem functions, including fire, food webs, and nutrient cycling, often require land areas of thousands of km^2, corridors can economically increase range sizes by linking up existing, but often small, management areas. Projects to reduce deforestation and degradation (REDD) can also serve to reduce fragmentation and to restore forest ecosystem services, including carbon sequestration.

Managing for habitat type rather than managing for specific species would involve the identification and conservation of functional groups (e.g., perennial grasses in a grassland ecosystem) or habitat types (e.g., tropical rainforest) instead of specific species. This potential adaptation measure recognizes that assuring the vibrant functioning of an ecosystem could more effectively conserve more species than dedicating scarce resources to the conservation of a few individual endangered species.

Monitoring ecosystem-level indicators, such as species richness, biomass, and densities of plants and animals, in permanent ecological plots will provide essential information to track impacts of climate change, ecosystem function, and the effectiveness of adaptation measures.

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