Chapter 4. Terrestrial and Inland Water Systems

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Executive Summary

There is *high confidence* that the magnitude of future climate change could approach that of many of the largest climatic changes observed in Earth history. There is also *high confidence* that the planet's biota, carbon cycle and associated feedbacks and services responded to this climate change, even when the rates of past global climate change were slower than implied by higher warming scenarios (e.g., RCP 8.5). [4.2.2] However, the impacts of climate change on terrestrial and freshwater ecosystems must also be considered in the context of non-climatic influences, both naturally-occurring and directly driven by humans. There is *high confidence* that most ecosystems change over time, due to biological interactions and natural environmental disturbances, even under climate change slower than projected for low- to medium-range warming scenarios (e.g., RCP2.6 to RCP6.0). [4.2.2]

Few ecosystems can now be considered to be unaffected by human activity. Vegetation cover classed as "primary" and essentially undisturbed by humans is estimated with *high confidence* to have decreased from approximately 95% of the global land area in 1500 AD to less than 40% at the start of the 21st Century, with half of this reduction being at the expense of primary forest. [4.2.1, 4.2.3, 4.2.4] **There is *medium confidence* that significant feedbacks exist between terrestrial ecosystems and the climate. Thus local, regional and global climate may be affected as ecosystems are altered, through climate change itself or other mechanisms, such as conversion to agriculture or human settlement.** These climate feedbacks are driven by changes in surface albedo, evapotranspiration and greenhouse gas emissions. The regions where the climate is affected may be different from the location of the ecosystem change. [e.g. 4.3.3.4]

There is *high confidence* for freshwater ecosystems and *medium confidence* for terrestrial ecosystems that direct human impacts such as land-use change, pollution and water resource development will continue to dominate the threats to ecosystems, with climate change becoming an increasing additional stress through the century, especially for high-warming scenarios such as RCP6.0 and RCP8.5. [4.3.3] Model-based projections imply that direct land cover change will continue to dominate over climate-induced change for low to moderate warming scenarios at global scales (e.g., RCP2.6 to RCP6.0). However, in many areas not subject to intensive human disturbance, there is *high confidence* that even lower levels of projected future climate changes will result in changes in large-scale ecosystem character depending on the nature of regional climate changes. Such changes may not be fully apparent for several decades after reaching the critical regional climate state, due to long response times in ecological systems (*medium confidence*). For higher warming scenarios, some model projections imply climate-driven large-scale ecosystem changes which become comparable with direct human impacts at the global scale (*medium confidence*). There is *high confidence* that rising water temperatures will lead to shifts in freshwater species distributions and compound water quality problems, especially in those systems experiencing high anthropogenic loading of nutrients. There is *medium confidence* that changes in precipitation will significant alter ecologically important attributes of flow regimes in rivers and wetlands and exacerbate impacts from human water use in developed river basins. [Box CC-RF, 4.3.3.3]

There is *high confidence* that the capacity of many species to respond to climate change will continue to be constrained by non-climate factors, including but not limited to the simultaneous presence of land-use changes, habitat fragmentation and loss, competition with alien species, exposure to novel pests and diseases, nitrogen loading, increasing carbon dioxide and tropospheric ozone. [Figure 4-1, 4.2.4-4.2.4.6, 4.3.3-4.3.3.5]

There is *high confidence* that a changing climate exacerbates other threats to biodiversity. In some systems, such as high altitude and latitude freshwater and terrestrial ecosystems, there is *high confidence* that climate changes exceeding those projected under RCP2.6 will lead to major changes in species distributions and ecosystem function. [4.3.2.5, 4.3.3.1, 4.3.3.3, 4.4.1.1] Since the specific changes in individual regions depends on the nature of the projected regional climate change, the confidence in specific future ecosystem changes is limited by the confidence assigned to regional climate change projections by Working Group I.

There is *high confidence* that plants and animal species have moved their ranges, altered their abundance and shifted their seasonal activities in response to climate change in the past. There is also *high confidence* that they are doing so now in many regions and will continue to do so in response to projected future climate change. [4.2.2, 4.3.2, 4.3.2.1, 4.3.2.5, 4.3.3] The broad patterns of species and biome movement towards the poles and higher in altitude in response to a warming climate are well established for the distant (*very high confidence*) and recent past (*medium confidence*). *High confidence* in these past responses, coupled with projections from a diversity of models and studies provide *high confidence* that such responses will be the norm with continued warming. [4.2.1, 4.2.2, 4.3.2, 4.3.2.1, 4.3.2.5] There is *high confidence* that these shifts in species ranges will cause large changes in local abundance under all climate change scenarios: abundance declining in areas where climate becomes unfavorable and potentially increasing in areas where climate becomes more favorable. [4.3.2.5] There is *high confidence* that such changes in species abundance lead to changes in community composition and ecosystem function. There is *high confidence*, based on extensive ground and satellite-based measurements that the seasonal activity of species has responded to warming over the last several decades. [4.3.2, 4.3.2.1, 4.4.1.1] Observations and models of the seasonal activities of species indicate that climate warming disrupts species life cycles and interactions between species, as well as altering ecosystem function. [4.3.2.1, 4.4.1.1] At local scales, observed and modelled species responses sometimes differ from qualitative predictions based on global scale indices of warming; this can often be explained by large variation in local scale climate response to global warming, changes in climate factors other than average temperature, non-climatic determinants of species distributions, interactions between climate and other simultaneous global change factors such as nitrogen deposition, and species interactions. [4.3.2.1, 4.3.2.5, 4.4.1.1] There is *high confidence* that no past climate changes is a precise analog to the current and projected climatic changes, so species responses inferred from the past only give indications, especially at the local scale. [4.2.2]

There is *high confidence* that climate change is increasing the likelihood of the establishment, growth, spread and survival of some invasive alien species populations in some regions. Alien invasive species are more likely than native species to have traits that favor their survival and reproduction under changing climates. Species movement into areas where they were not present historically will be driven both by climate change and by increased dispersal opportunities associated with human activities. [4.2.4.6]

There is *medium confidence* that even for mid-range rates of climate change (i.e., RCP4.5 and RCP6.0 scenarios) many species will be unable to move fast enough to track suitable climates. Over the last several decades many species have tracked changes in climate. However, there is *medium confidence* that some species have been unable to track recent climatic changes. [4.3.2.5] Populations of species that cannot track future climate change by migrating will find themselves in unfavorable climates and are unable to expand into newly climatically suitable areas. Species in large flat areas are particularly vulnerable because they must migrate over longer distances to keep up with climate change than species in mountainous regions. Species with low migration capacity will also be especially vulnerable: examples include most trees, many plants, and some small mammals. Combinations of low migration capacity and large flat areas are projected to pose the most serious problems for tracking climate; for example, there is *medium confidence* that even the maximum observed and modelled migration rates for mid- and late-successional tree species will be insufficient to track climate change in flat areas even at moderate rates of climate change. There is *high confidence* that barriers to migration such as mountain ranges, dams, habitat fragmentation and occupation of habitat by competing species substantially reduce the ability of species to migrate to more suitable climates. There is *high confidence* that outlier populations (e.g., collections in botanical gardens or parks), as well as intentional and accidental anthropogenic transport will speed migration. [4.3.2.5, 4.3.3.3]

There is *high confidence* that large magnitudes of climate change will negatively impact species with populations that are primarily restricted to protected areas, mountaintops or mountain streams, even those that potentially migrate fast enough to track suitable climates. [4.3.2.5, 4.3.4.1] Climate change is projected with *high confidence* to either create unsuitable climates for species that remain in these areas, or force species out of protected areas and off mountaintops. These effects are foreseen to be modest for low magnitudes of climate change (e.g., RCP 2.6) and very high for the highest magnitudes of projected climate change (e.g., RCP 8.5). There is *high confidence* that species have already started to migrate out of protected areas and towards mountaintops over the last several decades due to a warming climate. [4.3.2.5, 4.3.4.1]

There is *very high confidence* that projected climate changes imply increased extinction risk for a substantial fraction of species during and beyond the 21st century, especially as climate change interacts with other pressures. [4.3.2.5] Uncertainties in regional climate projections, highly variable estimates from comparisons of paleontological extinctions in response to past climate changes, different methods of estimating present and future extinction risk, and the variable adaptive capacity of wild species all contribute to an extremely broad range of estimates of future extinction risk due to climate change. There is *high confidence* that current extinction pressures from habitat modification, over-exploitation and invasive species are continuing, and will interact with growing impacts of climate change. When combined with methodological challenges in modelling future extinction risks, this means there is *low confidence* that global extinction risks due to climate change can be accurately quantified. There is, however, a strong consensus that current climate change pressures and their interactions with other global changes will increase extinction risk for many terrestrial and freshwater species. There is *very low confidence* that observed species extinctions can be attributed to recent climate warming given the very low fraction of species for which global extinction has been ascribed to climate change and tenuous nature of most attributions. However, in the specific case of Central American amphibians, there is *medium confidence* that recent warming has played a role in their extinctions. [4.3.2, 4.3.2.5]

It is *virtually certain* that the carbon stored in land and freshwater ecosystems in the form of plant biomass and soil organic matter has increased over the past two decades in what is known as the terrestrial carbon sink. There is *low confidence* that the transfer of carbon dioxide from the atmosphere to the land will continue at a similar rate for the remainder of the century. There is *high confidence* that the terrestrial carbon sink is offset to a large degree by carbon released to the atmosphere through forest conversion to farm and grazing land and through forest degradation [4.2.4.1, 4.3.3.1]. There is *medium confidence* that the carbon stored thus far in terrestrial ecosystems is vulnerable to loss back to the atmosphere as a result of climate change (including indirect effects such as increased risk of fires and pest outbreaks) and land-use change. Terrestrial and freshwater ecosystems have been responsible for the uptake of about a quarter of all anthropogenic CO_2 emissions in the past half century. [4.3.2.2 and 4.3.2.3] The net fluxes out of the atmosphere and into plant biomass and soils show large year-to-year variability. As a result there is *low confidence* in the ability to determine whether the net fluxes into or out of terrestrial ecosystems at the global scale have increased or decreased over the past two decades. There is *high confidence* that the factors causing the current increase in land carbon include the positive effects of rising CO_2 on plant productivity, a warming climate, and recovery from past disturbances, but *low confidence* regarding the relative contribution by each of these and other factors. [4.2.4.1, 4.2.4.2, 4.2.4.4, 4.3.2.2] Experiments and modelling studies provide *medium confidence* that increases in CO_2 up to about 600 ppm will continue to enhance photosynthesis and plant water-use efficiency, but at a diminishing rate. [4.2.4.4]. There is also *medium confidence* that other factors associated with global change, including high temperatures, rising ozone concentrations and in some places drought, decrease plant productivity by comparable amounts [4.2.4.3, Box 4-3]. Models provide *high confidence* that nitrogen availability will limit the response of many natural ecosystems to rising $CO_{2.}$ [4.2.4.2]. There are few field-scale experiments on ecosystems at the highest CO_2 concentrations projected by RCP8.5 for late in the century, and none of these include the effects of other potential confounding factors [4.3.2.2, 4.2.2.3].

There is *medium confidence* that increases in the frequency or intensity of ecosystem disturbances due to fires, pest outbreaks, wind-storms and droughts have been detected in many parts of the world. There is *high confidence* that such changes, which are by definition beyond the range of historical natural variability, will alter the structure, composition and functioning of ecosystems. There is *medium confidence* that such changes will often be manifested as relatively abrupt and spatially-patchy transitions following disturbances, rather than gradual and spatially-uniform shifts in location or abundance. [Box 4-3, Box 4-4, 4.2.4.6, 4.3.3, 4.3.2.5, Figure 4-12]

There is evidence of an increase in tree mortality in many regions over the last decade, but there is *low confidence* in the detection of a global trend in increased mortality or in the attribution of such a global trend to climate change. In some regions, increased tree mortality is sufficiently intense and widespread as to result in forest dieback. Forest dieback constitutes a major risk because of its large impacts on biodiversity, wood production, water quality, amenity, economic activity and the climate itself [4.3.2, 4.3.3.1, 4.3.3.4, 4.3.4, Box 4-2, Box 4-3]. In detailed regional studies, particularly in western and boreal North America, there is *high confidence* that observed tree mortality is detectable and can be attributed to the direct effects of high temperatures and drought, or to changes in the distribution and abundance of insect pests and pathogens related, in part, to warming.

Recent experimental, observational and modelling studies provide *medium confidence* that forests may be more sensitive to future climate change than reported in IPCC AR4 assessment and that tree mortality and forest dieback could become a problem in many regions much sooner than previously anticipated. [4.3.3.1] There is *high confidence* that future climate change impacts on tree mortality and tree ranges could be large, but experimental, observational and modelling studies also indicate that there is *low confidence* associated with model-based projections of the details of these impacts. As such, projections of increased tree growth and enhanced forest C sequestration mediated by increasing growing season length, rising CO_2 concentrations and atmospheric N deposition are being viewed with increasingly greater caution due to the counter-balancing effects of mortality and dieback. [4.3.3.1] The consequences for the provision of timber and other wood products are projected to be highly variable between regions and products depending on the balance of the positive vs. negative effects of global change. [4.3.3.1, 4.3.3.5, 4.3.4]

In the Amazon, there is *medium confidence* that climate change alone will not lead to widespread forest loss during this century. However, there is also *medium confidence* that a combination of severe drought, land use and fire act together to transform mature forests to less dense, fire prone woodland and shrublands. Modelling studies project a range of changes in the regional climate of the Amazon, and very few indicate a state that cannot support rainforest. Nevertheless, many models still project a general drying tendency, and coupled with warming this may increase fire risk. Human land use is associated with fire, so a combination of direct human influence and climate change may still affect the Amazon. [4.3.3.1.3, Box 4-3]

There is *high confidence* that terrestrial and freshwater ecosystems can, when pushed by climate change, cross "tipping points" and abruptly change in composition, structure and function. There is *medium confidence* that the crossing of these tipping points will result in significant increases in carbon emissions to the atmosphere. This has happened many times in Earth history. [4.2.2]. There are plausible mechanisms, supported by experimental evidence and model results, for the existence of ecosystem tipping points in both boreal-arctic systems and the rainforests of the Amazon basin [Boxes 4-3 and 4-4], others may exist. There is a plausible but *low confidence* case that continued climate change could push the boreal-arctic system across such a tipping point in this century and cause an abrupt transformation of the ecology and albedo of this region, as well as the release of greenhouse gases from the thawing permafrost and burning forests. There is *high confidence* that adaption measures will be unable to prevent substantial change in the boreal-arctic system. There is also a plausible but *low confidence* case that continued climate change together with land-use change and fire activity could cause much of the Amazon forest to transform abruptly to more open, dry-adapted ecosystems, and in doing so, put a large stock of biodiversity at elevated risk, and create a large new net greenhouse gas source to the atmosphere. [4.3.3.1]. There is *medium confidence* that the combination of climate change and land-use change in the Amazon will cause accelerated drying and drought frequency in the region and *low confidence* that these Amazon changes will affect rainfall in agricultural regions elsewhere on the planet. [4.3.3.1]. There is *medium confidence* that rigorously applied adaptation measures could lower the risk of abrupt change in the Amazon, as well as the impacts of that change. [Box 4-3, 4.3.3-4.3.3.4, Figure 4-10]. There is *very high confidence* that policy and market-driven interventions have caused a steep decline in deforestation in the Amazon since 2005 that have decreased anthropogenic carbon emissions to the atmosphere by 1.5%. [4.2.4.1, 4.3.3.1]

There is *high confidence* that management actions can reduce, but not eliminate, exposure to climate-driven ecosystem impacts, as well as increase ecosystem adaptability. [4.4] The capacity for natural adaptation by ecosystems and their constituent organisms is substantial, but for many ecosystems and species there is *medium confidence* that this is insufficient to cope without substantial loss of species and ecosystem services, given the rate and magnitude of climate change projected under medium-range warming (e.g., RCP6.0) or high–range warming scenarios (e.g., RCP8.5). The capacity for ecosystems to adapt to climate change can be increased by reducing the other stresses operating on them; reducing the rate and magnitude of change; reducing habitat fragmentation and increasing connectivity; maintaining a large pool of genetic diversity and functional evolutionary processes; assisted translocation of slow moving organisms or those whose migration is impeded, along with the species on which they depend; and manipulation of disturbance regimes to keep them within the ranges necessary for species persistence and sustained ecosystem functioning. [4.4.1-4.4.1.2, 4.4.3]

There is *medium confidence* that management adaptation responses to climate change in some sectors will lead to unintended and unwanted outcomes for terrestrial and freshwater ecosystems. For example, adaptation responses to counter increased variability of water supply for urban and agricultural use, such as building more and larger impoundments and increased water abstraction, will compound the direct effects of climate change in freshwater ecosystems. [4.3.3.3, 4.3.4.5**] There is *very high confidence* that the use of the terrestrial biosphere in climate mitigation actions, such as through introduction of fast-growing tree species for carbon sequestration or the conversion of forest to biofuel plantations, may lead to negative impacts on ecosystems and biodiversity.** The land use scenario accompanying the mitigation scenario RCP2.6, intended to avoid 2°C global warming, features large expansion of biofuel production, displacing natural forest cover. [4.2.4.1]

4.1. Past Assessments

The topics assessed in this chapter were last assessed by the IPCC in 2007, principally in the Working Group II report chapters 3 (Freshwater resources and their management; Kundzewicz *et al.*, 2007) and 4 (Ecosystems, their properties, goods and services; Fischlin *et al.*, 2007). Together they found that 'Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases'. Although circumstantial evidence was offered that anthropogenic climate change was a cause of the observed changes, it was not possible to attribute a relative proportion of the changes to this cause with any confidence. An important finding was that 20-30% of the plant and animal species that had been assessed to that time were considered *likely* to be at increased risk of extinction if the global average temperature increases exceeded 2-3°C. Fischlin *et al.* (2007) also stated that substantial changes in structure and functioning of ecosystems (terrestrial, marine and other aquatic) are *very likely* under a warming of more than 2-3°C above pre-industrial levels. No timescale was associated with these findings. The report noted that vulnerability to climate change could be exacerbated by the presence of other stresses, such as pollution.

4.2 A Dynamic and Inclusive View of Ecosystems

Ecologists no longer view ecosystems as inherently unchanging unless perturbed by an externally originating disturbance (Hastings, 2004). A growing body of both theory and observation (Scheffer, 2009) supports the emerging view that most ecosystems vary substantively over time in the relative magnitude of their components and fluxes, even under a relatively constant environment. Furthermore, attempts to restrict this intrinsic variation - or that resulting from imposed disturbances - are frequently futile, and may damage the capacity of the ecosystem to adapt to changing environments (Folke *et al.*, 2004). Contemporary treatments of ecosystems treat humans as an integral part of the system, rather than as an external perturbation to the natural state without any feedback to the human system itself (Gunderson and Holling, 2001). The emerging view is of relatively tightly coupled social-ecological systems, which means that their joint dynamics are governed not only by biophysical processes such as energy flows, material cycles, competition and predation, but also by social processes such as economics, politics, culture and individual preferences (Walker and Salt, 2006).

4.2.1. Ecosystems as Adaptive Entities

There is increasing focus on how ecosystems behave in the vicinity of their environmental limits, rather than solely on their behavior near the middle of their domain of their inferred preferred state (Scheffer *et al.*, 2009). The notion of thresholds has become a prominent ecological and political concern (Lenton *et al.*, 2008; Knapp et al 2008, Scheffer *et al.*, 2009; Leadley *et al.*, 2010). Some thresholds reflect a human preference that the ecosystem stays within certain bounds. Others reflect fundamental biophysical properties, for instance the thawing of frozen soils (see Box 4-4); or the physiological tolerance limits of constituent species. A third category of threshold relates to system dynamics under externally-driven change: the point at which the net effect of all the positive and negative feedback loops regulating the ecosystem is positive, causing a small perturbation to become amplified sufficiently to lead to a change in ecosystem state, from which it will not spontaneously return in the short term. The new state will typically exhibit different dynamics, mean composition, sensitivity to environmental drivers and flows of ecosystem services relative to the prior state. This type of threshold is called a tipping point (see glossary).

The early detection and prediction of ecosystem thresholds, particularly tipping points, is an area of active research. There are indications (Scheffer, 2009) that an increase in ecosystem variability signals the impending approach of a threshold.In practice, such signals may not be detectable against background noise and uncertainty until it is too late to avoid the threshold (Biggs *et al.*, 2009). The dynamics of ecosystems are complex and our present level of knowledge is often inadequate to predict an ecosystem outcome with confidence, even if the future climate was precisely known.

The term 'resilience'(see glossary) has attracted a range of meanings in different disciplines. In ecology it is used both in the sense of 'a measure of the ability of these systems to absorb changes of state variables, driving variables and parameters, and still persist' (Holling, 1973), and also in a broader sense of being able to adapt to change, without necessarily remaining within the same dynamical range (Walker *et al.*, 2004) and has been applied in the context of climate change (e.g. Morecroft *et al.*, 2012). One source of such adaptability is evolution within the populations of organisms making up the ecosystem. Natural selection operates on genetic variability against those individuals less able to survive, compete and successfully reproduce in the altered environment, leading to a shift, over generations, in the tolerance range of the population. Organisms also typically exhibit physiological, developmental or behavioral plasticity, within limits, that does not require genetic change. A particular case occurs when humans in the ecosystem use learning and technology to alter how they interact with the system. A third form of adaptation occurs when the configuration and functional form of interactions within an ecosystem change, in some cases leading to a new stable state (www.regimeshifts.org). It occurs when the abundance of one or more species are greatly altered or are replaced by other species with similar functional attributes. In the extreme, this would constitute a change in ecosystem type.

Field observations over the past century in numerous locations in boreal, temperate and tropical ecosystems have detected shifts of plant species at the biome level upwards in elevation and to higher latitudes (Gonzalez *et al.*, 2010). These shifts have been formally or informally attributed to climate change ([INSERT TABLE 4-1 HERE Table 4-1, Figure 4-1). Projections of potential future vegetation indicate substantial susceptibility of ecosystems to biome shifts (Warszawski *et al*, submitted; Figure 4-2, Box 4-3, Box 4-4).

[INSERT TABLE 4-1 HERE
Table 4-1: Biome shifts from 1700 to the present from published field research that examined trends over periods > 30 y for biomes in areas where climate (rather than land-use change or other factors) predominantly influenced vegetation, derived from a systematic analysis of published studies (Gonzalez *et al.* (2010). Pre-AR4 publications are included to provide a comprehensive review. Shift type: elevational (E), latitudinal (L), examined but not detected (N). Biomes (and abbreviations), from poles to equator: tundra and alpine (UA), boreal conifer forest (BC), temperate conifer forest (TC), temperate broadleaf forest (TB), temperate shrubland (TS), tropical grassland (RG), tropical woodland (RW). Rate of change in temperature (Temp.) and fractional rate of change in precipitation (Precip.) are derived from linear least squares regression of 1901-2002 data (Mitchell and Jones, 2005; Gonzalez *et al.*, 2010). The table provides general regional climate trends at 50 km spatial resolution because the references do not give uniform site-specific climate data to compare across locations. The regional trends are consistent with local trends reported in each reference. * rate significant at $P \leq 0.05$).]

[INSERT FIGURE 4-1 HERE
Figure 4-1: Biome shifts from 1700 to the present at sites in Table 4-1, derived from Gonzalez *et al.* (2010). Temperature change is the rate from linear least squares regression of 1901-2002 temperatures (Mitchell and Jones, 2005; Gonzalez *et al.*, 2010). Numbers refer to the sites in Table 4-1. Arrows indicate general direction of shifts.]

[INSERT FIGURE 4-2 HERE
Figure 4-2: Fraction of land surface at risk of severe ecosystem change as a function of global mean temperature change for all ecosystems models, global climate models and RCPs. The colors represent the different ecosystems models, which are also horizontally separated for clarity. Results are collated in unit-degree bins, where the temperature for a given year is the average over a 30-year window cente4red on that year. The median in each bin is denoted by a black horizontal line. The grey boxes span the 25th and 75th percentiles across the entire ensemble. The short, horizontal stripes represent individual (annual) data points; the curves connect the mean value per ecosystem model in each bin. The solid (dashed) curves are for models with (without) dynamic vegetation composition changes. Right: Fraction of global land surface subject to severe ecosystem change as a function of global mean temperature (left panels) and time (right panels) for the JeDi (upper) and JULES (lower) dynamic global vegetation model driven by the HadGEM2-ES global climate model. The colors represent the different RCPs used to drive the climate model. Good agreement of results at different levels of global warming demonstrates that results are independent of the emissions scenario. (Reproduced from Warszawski *et al.*, submitted)]

4.2.2. What the Paleoecological Record Can and Cannot Tell Us

Paleoclimatic observations and modelling indicate that the Earth's climate has always changed on a wide range of time-scales. In many cases, particularly over the last million years, it has changed in ways that are well-understood in terms of both patterns and causes, (Jansen *et al.*, 2007; IPCC AR5 WGI Chapter 5). Independent paleoecological records demonstrate with *high confidence (robust evidence, high agreement)* that the planet's biota (both terrestrial and aquatic), carbon cycle and associated feedbacks and services have responded to this climatic change, particularly when the climatic change was as large as projected future mid- to high-end change (e.g., MacDonald *et al.*, 2008; Claussen, 2009; Arneth *et al.*, 2010; Willis and MacDonald, 2011; Dawson *et al.*, 2011). Excellent examples of past large climate change events that drove large ecological change include the events that led to the Earth's five mass extinctions in the distant past (i.e., during the Ordovician, ca. 443 Ma, the Devonian, ca. 359 Ma, the Permian, ca. 251 Ma, the Triassic, ca. 200 Ma, and the Cretaceous, ca. 65 Ma; Barnosky *et al.*, 2011). Major ecological change was also driven by climate change during the Paleocene-Eocene Thermal Maximum (PETM, 56 Ma; Wing *et al.*, 2005; Jaramillo *et al.*, 2010), the early Eocene Climatic Optimum (EECO, 53-50 Ma; Woodburne *et al.*, 2009), the Pliocene (5.3 to 2.6 Ma; Haywood and Valdes, 2006; Haywood *et al.*, 2011), and the Last Glacial Maximum (LGM; 21 ka) to Holocene (11 ka) transition (MacDonald *et al.*, 2008; Clark *et al.*, 2009; Gill *et al.*, 2009; Williams *et al.*, 2010b; Prentice *et al.*, 2011; Daniau *et al.*, 2012). The paleoecological record thus provides *high confidence (robust evidence, high agreement)* that large climate change, such as that projected for the 21st century, can result in large ecological changes, including large scale biome shifts, reshuffling of communities and, potentially, species extinctions.

Rapid, regional warming before and after the Younger Dryas cooling event (11.7-12.9 ka) provides a relatively recent analogy for climate change at a rate of a speed that approaches that projected for the 21st century (Alley *et al.*, 2003; Steffensen *et al.*, 2008). Ecosystems and species responded rapidly during this period by shifting distributions and abundances, and there were some notable large animal extinctions, probably exacerbated by humans activities (Gill *et al.*, 2009; Dawson *et al.*, 2011). In some regions, species became locally or regionally extinct, but there is no evidence for climate-driven large-scale extinctions during this period of rapid climate change (Botkin *et al.*, 2007; Willis *et al.*, 2010c), except for a small number of plant species (Jackson and Weng, 1999; Birks and Willis, 2008). However, these climate excursions differ from those projected for the future because they were regional rather than global; may have only regionally exceeded rates of warming projected for the future; and started from a baseline substantially colder than present (Alley *et al.*, 2003). The mid-Holocene around ca. 6 ka provides a very recent example of the effects of modest climate change, because regional warming during this period (ca. 0.5-1.5°C above pre-industrial temperatures in some regions) was the same order of magnitude as the warming the Earth has experienced over the last century. Ecological effects were small compared to periods with larger climate excursions, but even this small degree of warming was characterized by frequent fires in a drier Amazon (Mayle and Power, 2008), development of lush vegetation and lakes in a wetter Sahara (Watrin *et al.*, 2009), temperate deciduous forests in Europe expanding further north and up to higher elevations (Adamik and Kral, 2008), and large-scale migration of Boreal forest into a warmer tundra (Jackson and Overpeck, 2000). Past climate change, even more modest than mid-range projected future change, has also clearly impacted inland water systems (e.g., Smol and Douglas, 2007b; Battarbee *et al.*, 2009; Beilman *et al.*, 2009). However, there are no exact analogues for future climate change: none of the well-studied past periods of large climate change involved simultaneously the rates, magnitude and spatial scale of climate change projected for the next century and beyond (Jansen *et al.*, 2007; Schulte *et al.*, 2010; IPCC AR5 Chapter 5). Direct analogy with the paleoecological record is also unwarranted because future climate change will interact with other global changes such as land-use change, invasive species, pollution and overexploitation of natural resources (Pereira *et al.*, 2010). There is *high confidence (robust evidence, high agreement)* that these interactions will also be important: the paleoecological record provides *medium confidence* (*medium evidence, high agreement*) that exploitation by humans helped drive many large mammal species to extinction during periods of climate change in past (Lorenzen *et al.*, 2011).

It has been demonstrated that state-of-the-art vegetation models are able to simulate much of the biome-level equilibrium response of terrestrial to large paleoclimate change (Prentice *et al.*, 1996; Salzmann *et al.*, 2008; Prentice *et al.*, 2011). These same types of models predict large changes in species ranges, ecosystem function and carbon storage when applied to 21st century climate change (Sitch *et al.*, 2008; Cheaib *et al.*, 2012). Thus, the paleoecological record, and models that have been tested against that record provide a coherent message that biomes will move, species mixtures will change, novel new plant communities will emerge, and significant carbon changes will take place, all in response to changing and often novel future climates (Williams and Jackson, 2007; Williams *et al.*, 2007b; MacDonald, 2010; Prentice *et al.*, 2011; Willis and MacDonald, 2011); see Section 4.3.2.5 for more specific information on migration rates). As such, the paleoecological record and models provide *high confidence (robust evidence, high agreement)* that it will be difficult or impossible to maintain many ecological systems in their current states if global warming exceeds 2 to 3°C, raising questions about the long-term viability of some current protected areas and conservation schemes, particularly where the objective is to maintain present-day species mixtures (Jackson and Hobbs, 2009; Hickler *et al.*, 2012).

Much of the complex, time-dependent change at regional scales has not yet been simulated by models. The paleoecological record indicates that vegetation in many parts of the world has the potential to respond within years to a few decades to climate change (e.g., Watrin *et al.*, 2009; Williams *et al.*, 2009; Mueller *et al.*, 2009a; Harrison and Goni, 2010), and this same record thus provides a critical model evaluation opportunity that should be more thoroughly exploited to gain confidence in time-dependent simulations of future change, particularly given the complex role that interacting climate change and vegetation disturbance has played in the past (e.g., Marlon *et al.*, 2009; Jackson *et al.*, 2009; Williams *et al.*, 2009; Daniau *et al.*, 2010; Dawson *et al.*, 2011).

The paleoclimatic record also reveals that past radiative climate forcing change was slower than that anticipated for the 21st century (IPCC AR5 Chapter 12), but even these slower changes often drove surprisingly abrupt, or non-linear, regional change in terrestrial and aquatic systems (e.g., Harrison and Goni, 2010; Williams *et al.*, 2011), as did even slower orbitally-driven change during the most recent Holocene interglacial (e.g., Booth *et al.*, 2005; Kropelin *et al.*, 2008; Williams *et al.*, 2010b; Williams *et al.*, 2011). In all cases, specific periods of abrupt ecological response were regionally distinct in nature and were less synchronous for small, slow changes in forcing (e.g., during the Holocene) than for more global rapid changes listed at the start of this section. State-of-the-art climate and Earth system models are unable to simulate the full range of abrupt change observed in many of these periods (e.g., Valdes, 2011) and thus there is *medium confidence* (*medium evidence*, *medium agreement*) that these models may not capture some aspects of future climate change and associated ecosystem impacts (Leadley *et al.*, 2010).

4.2.3. Landscapes and Social-Ecological Systems

Ecosystems do not exist in isolation from one another or from human systems. Landscapes, which consist of multiple interacting ecosystems, all experience some degree of interaction with people. The responses of terrestrial and freshwater ecosystems to climate change are therefore mediated by human activities at a range of spatial and temporal scales, and to varying degrees. Together, the social and ecological elements form a linked system (a ‘social-ecological system, SES) in which the degree of coupling can range from very close to slight (Berkes *et al.*, 2003).

4.2.4. Multiple Stressors and the Role of Climate Change

While isolated effects of the main drivers of global change (e.g. climate change, habitat loss, chemical pollution and biological invasions) are increasingly well documented (Millennium Ecosystem Assessment, 2005b; Settele *et al.*, 2010a) there is much less knowledge about their consequences when acting in combination. Multiple stressors can act in a non-additive way (Settele *et al.*, 2010b; Shaw *et al.*, 2002; Larsen *et al.*, 2011), potentially invalidating findings and interventions based on single-factor analysis. In a multifactorial climate change experiment Larsen *et al.*, 2011), demonstrated that non-additive interactions among the climate factors were frequent but most often antagonistic leading to smaller effects than predicted from the single factor effects. Leuzinger *et al.*, (2011) and Dieleman *et al.*, (2012) have synthesized such multifactor interactions and demonstrated that in general, the effect size appears to be reduced when more factors are involved. Leuzinger *et al.* (2011) further showed that models tend to show the opposite trend.

Climatic and non-climatic drivers of ecosystem change must be distinguished if the joint and separate attribution of changes to their causes is to be performed – of paramount importance if the processes of change are to be understood and future changes predicted. Within this section we elaborate on drivers and stressors which often act in concert with climate change, ranging from a high degree of relatedness to climate change (rising CO_2; tropospheric ozone; total, diffuse and UV radiation), over intermediate (land-use change) to low degrees of relatedness (invasive species and N deposition).

4.2.4.1. Land-Use and Cover Change (LUCC)

Land use and land cover continues to change worldwide. In tropical and subtropical areas of Asia, Africa, Oceania and South America, the most widespread land-use changes are conversion of forests and woodlands to annual and perennial agriculture, grazing pastures and commercial plantations, followed by conversion of grasslands and pastures to annual agriculture. Afforestation at the expense of agricultural lands is more frequent in Europe (Rounsevell and Reay, 2009; Schwaiger and Bird, 2010; Miyake *et al.*, 2012) and loss of agricultural land to urban settlements is common in both the developed and developing world. LUCC is both a cause and consequence of climate change. The underlying drivers of LUCC include rising demand for food, fiber and bioenergy, and changes in lifestyle and technologies – some of which are also drivers of climate change. In the future climate change is projected to become a major driver of land cover change and ecosystem functioning, with more than a quarter of the land surface projected to be at risk of severe ecosystem change at global warming of 4°C or above (Figure 4-2). Land cover change can also be caused by change in non-climate environmental drivers such as nutrient loading, pollution and disturbance regimes.

The cause-and-effect entanglement of climate change and LUCC make attribution of consequences to one or the other very difficult. In 13 of the 24 regional land use studies reviewed for this chapter, local-to-regional climate change was at least partly attributed to LUCC, generally with *limited evidence* and *low confidence*. (Direct climate effects attributed to LUCC: Tseng and Chen, 2008; Cui and Graf, 2009; Li *et al.*, 2009; McAlpine *et al.*, 2009; Zhang *et al.*, 2009; Fall *et al.*, 2010; Graiprab *et al.*, 2010; Jin *et al.*, 2010; Mishra *et al.*, 2010; Schwaiger and Bird, 2010; Wu *et al.*, 2010; Gao and Liu, 2011; Carmo *et al.*, 2012. No climate effects attributed: Suarez *et al.*, 1999, Saurral *et al.*, 2008; SuFen *et al.*, 2008; Cochrane and Barber, 2009; Jia *et al.*, 2009a; Rounsevell and Reay, 2009; Martin *et al.*, 2010, Wiley *et al.*, 2010; Clavero *et al.*, 2011; Dai *et al.*, 2011; Viglizzo *et al.*, 2011; Yoshikawa and Sanga-Ngoie, 2011).

LUCC contributes to climate change through changes in the sources or sinks of greenhouse gases and through changes in the absorption of solar energy by the land surface. These factors can have opposite effects and operate at different scales. For instance, conversion of forest to non-forest generally releases carbon dioxide from biomass and soils to the atmosphere, causing warming globally; but also often results in an increase in seasonally-averaged albedo, causing cooling locally and globally (Davin *et al.*, 2007), and a decrease in transpiration, causing warming locally but not globally. Four out of five global climate models suggested local cooling effects following forest conversion to croplands and pastures (Pitman *et al.*, 2009). Equilibrium experiments with the GDFL climate model (Findell *et al.*, 2007) concluded that the land-use change driven climatic impacts *not* mediated by greenhouse gases were generally minor, but significant in a few regions (Eastern Europe, Northern India, and Eastern China). More substantial global effects were projected by van der Molen *et al.* (2011) who found little temperature response to change from forests to pasture or crops in the tropics, increasing towards the Northern Hemisphere mid-latitudes. In high latitudes, changes in snow cover exposure and duration contribute to the albedo increase following forest clearing (Mishra *et al.*, 2010, Levis, 2010).

Afforestation programs are often recommended to promote carbon sequestration (e.g. Fiorese and Guariso, 2013; Singh *et al.*, 2013) but over the long term afforestation may lead to a slight net global warming when the albedo increase effect neutralizes the carbon uptake effect (Schwaiger and Bird, 2010). Wickham *et al.*, (2012) found significant positive slopes in regressions of average annual surface temperatures versus the proportion of forest and argue that the value of temperate afforestation as a potential climate change mitigation strategy is unclear. Changes in albedo, other biophysical effects and some indirect greenhouse effects (such as changes in soil erosion), are not currently included in the formal rules for accounting for the climate effects of land use activities (Schwaiger and Bird, 2010; Kirschbaum *et al.*, 2012).

The reported effects on precipitation of conversion of forest to pastures and crops vary. Many studies report rainfall decreases, soil moisture decreases and changes in rainfall pattern (e.g. Nepstad *et al.*, 2008; McAlpine *et al.*, 2009; Mendelsohn and Dinar, 2009; Eliseev and Mokhov, 2011). In some cases forest clearing has been reported to enhance local rainfall. Garcia-Carreras and Parker (2011) suggest that enhanced local precipitation can occur over deforested patches due to breezes between forest and cropland. Enhanced rainfall over vegetation boundaries has been shown to occur both in the Amazon (e.g. Knox *et al.*, 2011) and in West Africa (e.g. Garcia-Carreras *et al.*, 2010) as a result of mesoscale processes that are currently not resolved in General Circulation Models.

In China, Han *et al.*, (2012) compared historical data from 244 weather stations predominantly surrounded by cultivated land and 195 stations surrounded by with >70% natural cover. They observed a greater decrease in potential evaporation at stations with significant agricultural influence. In arid and semi-arid regions this was associated with a decrease in wind speed, increase in relative humidity and increase in air temperature compared with natural stations; while in humid and sub-humid regions it was associated with increased wind speed and decreased solar radiation.

Several assessments conclude that LUCC, acting through habitat loss and fragmentation, is the largest cause of contemporary terrestrial and freshwater biodiversity loss, with climate change becoming an increasingly important factor later in the 21st century (Millennium Ecosystem Assessment, 2005a; http://www.cbd.int/gbo3/).

_____ START BOX 4-1 HERE _____

Box 4-1. Future Land Use Pathways and Their Uncertainties

Assessment of climate change effects on terrestrial and inland freshwater ecosystems is incomplete in the absence of information on the direct impacts of people on these systems through land use. The world is undergoing important shifts in land-use patterns. Growth in demand for food, feed, fiber, and fuel has accelerated in recent years, placing new pressures on terrestrial and freshwater ecosystems and outpacing the growth in supply. The principal driver of this acceleration in demand is the rate at which per capita consumption is growing in emerging economies (Tilman *et al.*, 2011). Policy shifts in OECD countries favoring the expansion of biofuel production have contributed to this acceleration (Lapola *et al.*, 2010; Searchinger *et al.*, 2008; Miyake *et al.*, 2012). Growth in demand that outpaces growth in supply, climate-related crop failure (Lobell *et al.*, 2011), declines in the growth of agricultural productivity (Ray *et al.*, 2012) and possibly a shortage of arable land that is not already under cultivation, especially in the temperate zone (Lambin and Meyfroidt, 2011) are all contributing to a rise in commodity prices that may persist through 2020 (OECD/FAO, 2010) and growing pressure on as-yet uncultivated ecosystems on soils that are potentially suitable for cultivation and that are concentrated in tropical latitudes, especially South America and Africa.

Emerging economies start from a relatively low per capita consumption base. The growth of these economies will therefore play an important role in future land use trends. Deforestation in developing countries is now correlated with the export of agricultural commodities (DeFries *et al.*, 2010), providing an early sign of the growing role of agricultural trade with emerging economies as a driver of land-use change. The trajectory of future growth in demand for land- and freshwater-based production remains uncertain, since it depends on economic trends and policies, which are themselves dependent upon complex political and social processes. One of the uncertainties about future land use trends is climate policy. Deforestation rates in the Brazilian Amazon declined 76% (as of 2012) below its ten-year average as a result of policy and market signals (Soares-Filho *et al.*, 2010); this single trend represents a 1.5% reduction in global anthropogenic carbon emissions (Nepstad *et al.*, in press).

These land use trends and the global land cover patterns that they promote have been simulated and mapped within a global grid as input to the Regional Concentration Pathways (RCPs) in preparation for the IPCC AR5. The 4 main RCPs used for future climate projections are accompanied by spatially-explicit future land use scenarios consistent with the emissions scenario and the associated socio-economic scenario (Hurtt *et al.*, 2011) generated by Integrated

Assessment Models using simple methodologies intended to capture the main processes at continental and global scales.

[INSERT TABLE 4-2 HERE
Table 4-2: Summary of drivers and outcomes of land use / cover scenarios associated with Representative Concentration Pathways (Hurtt et al., 2011).]

In the RCPs, land cover change is driven by a number of socioeconomic drivers, including climate policy. The nature of climate policy effects on land use differs between RCPs, with some climate mitigation policy scenarios including conservation of primary vegetation (natural, mature ecosystems) as carbon sinks while others included replacement of primary vegetation with biomass and / or biofuel plantations. The extent to which primary vegetation is replaced by secondary vegetation, crops or pasture also varies between the RCPs (Figure 4-3), but there is no simple linear relationship between the extent of vegetation change and the level of total radiative forcing arising from all sources. Larger reductions in primary vegetation cover are seen in RCP8.5 (the highest emissions scenario) due to a general absence of pro-active measures to control land cover change, but large reductions were also seen in RCP2.6 (an aggressive mitigation scenario with low emissions) due to widespread conversion of land to biomass and biofuel crops coupled with carbon capture and storage. Smaller reductions were seen in RCP6.0 and RCP4.5, with the latter involving conservation of primary forest or regrowth of secondary forest as a mitigation measure. Hence both the highest and lowest emissions scenarios were associated with greater extents of land cover change.

[INSERT FIGURE 4-3 HERE
Figure 4-3: Proportion of global land cover occupied by primary and secondary vegetation (forest and non-forest), cropland, pasture and urban land, from satellite data and historical reconstructions up to 2005 (KleinGoldewijk, 2001), and from scenarios associated with the RCPs from 2005 to 2100 (Hurtt *et al.*, 2011).]

Spatial patterns of the future land cover change in all RCPs were largely similar to patterns of historical change (Figure 4-4) as most future change is projected to be a continuation of past change. By definition, primary vegetation cover cannot increase on the timescales considered here, so in scenarios where cropland and pasture are projected to decrease, these are replaced with secondary vegetation. Both tropical and boreal forest regions are projected to undergo declining primary forest cover in all 4 RCPs, but in RCP6.0 total forest area remains approximately constant.

[INSERT FIGURE 4-4 HERE
Figure 4-4: Fractional cover of primary vegetation at 1850, 2005 based on satellite data and historical reconstructions (KleinGoldewijk, 2001) and at 2100 in scenarios associated with the RCPs (Hurtt *et al.*, 2011).]

_____ END BOX 4-1 HERE _____

4.2.4.2. Nitrogen Deposition

The global nitrogen (N) cycle has been strongly perturbed by human activity over the past century (Gruber and Galloway, 2008; Sutton *et al.*, 2011). Human activities currently transform 160 TgN/year of nitrogen gas in the atmosphere into reactive forms of N that can be readily used by plants and microorganisms in land and in the ocean (Galloway *et al.*, 2008). This is close to the pre-industrial global flux of about 255 TgN/year from all natural sources. The human-caused flow from land to the coastal oceans in rivers is about 50 TgN/y, additional to the estimated natural flux of 30 TgN/year (Galloway *et al.*, 2008). Many of the sources of additional reactive nitrogen share root causes with changes in the carbon cycle - such as increased use of fossil fuels and expansion and intensification of global agriculture - so N deposition, rising CO_2 concentrations and warming are increasing together at global scales (Steffen *et al.*, 2011). This large addition of reactive N into the biosphere can reinforce global warming (e.g., though emission of N_2O associated with fertilizer manufacture and application), or diminish warming (e.g., by increasing C storage in many terrestrial ecosystems). The balance of these effects is difficult to estimate (Erisman *et al.*, 2011; WG1 chapter 6; Hanson *et al.*, 2005). Regional trends in N fluxes differ substantially: N fertilizer use and N deposition are stable or declining in some regions, such as Western Europe; but

N deposition and its impacts on biodiversity and ecosystem functioning are projected to increase substantially over the next several decades in other regions, especially in regions dominated by rapidly-growing emerging economies (Galloway *et al.*, 2008).

Experiments and observations, most of which are in temperate and boreal Europe and North America, show a consistent pattern of increase in the dominance of a few nitrogen-loving plant species and loss of overall plant species richness at N deposition loads exceeding between 5 and 20 kgN/ha/year (Bobbink *et al.*, 2010; but see Stevens *et al.*, 2010a). N deposition is currently above these limits in much of Europe, eastern North America, and Southern Asia (Galloway *et al.*, 2008), including in many protected areas (Bleeker *et al.*, 2011). Experiments examining the interactive impacts of N deposition and elevated CO_2 or climate change on natural systems have increased in number since the AR4, but remain few (Rustad, 2008). Recent studies show that interactions between nitrogen and other global change factors are widespread, strong and complex (Thompson *et al.*, 2008; Langley and Megonigal, 2010; Gaudnik *et al.*, 2011; Hoover *et al.*, 2012; Eisenhauer *et al.*, 2012; but see Zavaleta *et al.*, 2003a for evidence of additive effects). For example, combinations of treatments mimicking future N deposition, elevated CO_2 concentrations and warming had larger negative impacts on pollinator populations than could be predicted from individual treatments (Hoover *et al.*, 2012). Analyses using the multi-factor biodiversity change model GLOBIO3 suggest that N deposition will continue to be a significant contributing factor to terrestrial biodiversity loss in the first third of the century but will be a less important factor than climate change in this period, and a much smaller driver than habitat loss due expansion of agricultural lands (Alkemade *et al.*, 2009). Models that explicitly take into account interactive effects of climate change and N deposition on plant communities project that N deposition impacts will continue to be important, but climate change effects will begin to dominate other factors by the middle of the 21st century (Belyazid *et al.*, 2011).

The impacts of N deposition are often first manifested in freshwater ecosystems, since they collect and concentrate the excess N (and phosphorus) from the land, as well as from sewage and industrial effluents. Primary production in freshwater ecosystems can be either N and P limited or both (Elser *et al.*, 2007), but the biodiversity and capacity of freshwater ecosystems to deliver high quality water, recreational amenity and fisheries services is severely reduced by the addition of nutrients beyond their capacity to process them. Excessive loading of N and P is widespread in the lakes of the northern hemisphere (Bergstrom and Jansson, 2006). The observed symptoms include a shift from nitrogen limitation of phytoplankton in lakes to phosphorus limitation (Elser *et al.*, 2009).

Since the AR4 report there has been an increase in the number of studies using models, observations and experiments to understand and predict the interactive effects of N deposition, climate change and CO_2 on ecosystem function. Broadly, this research shows that ecosystem function is mediated by complex interactions between these factors, such that many ecosystem responses remain difficult to understand and predict (Norby and Zak, 2011; Churkina *et al.*, 2010). For example, experiments, observations and models suggest that the observed increase in productivity and carbon storage in forests in many parts of the world is due to combinations of N deposition, climate change, fertilization effects of rising CO_2, and forest management (Magnani *et al.*, 2007; Huang *et al.*, 2007; Pan *et al.*, 2009; Churkina *et al.*, 2010; Bontemps *et al.*, 2011; Bellassen *et al.*, 2011; de Vries and Posch, 2011; Eastaugh *et al.*, 2011; Norby and Zak, 2011; Shanin *et al.*, 2011; Lu *et al.*, 2012). Despite difficulties in quantifying the relative contributions of these factors and their interactions, it appears that the effects of N deposition and rising CO_2 have generally dominated to date in much of the Northern hemisphere, however, the direct effects of rising temperature and changes in precipitation are may exceed N and CO_2 as key drivers of ecosystem primary productivity in a few decades time. On the other hand, experiments in grasslands show that plant productivity is increased more by N addition (within the projected range for this century) than by elevated CO_2, also within its projected range; and that N effects increase with increasing precipitation (Lee *et al.*, 2010). In contrast to forests and temperate grasslands, N deposition and warming can have negative effects on productivity in other terrestrial ecosystems, such as moss-dominated ecosystems (Limpens *et al.*, 2011). The interactions between N deposition and climate change remain difficult to understand and predict (Ma *et al.*, 2011; Menge and Field, 2007), in part due to shifts in plant species composition (Langley and Megonigal, 2010) and the complex dynamics of coupled C, N and P cycles (Menge and Field, 2007; Niboyet *et al.*, 2011).

4.2.4.3. Tropospheric Ozone

The concentration of ozone in the troposphere (the part of the atmosphere adjacent to terrestrial ecosystems) has been rising over the past 160 years (Horowitz, 2006; Oltmans *et al.*, 2006; Cooper *et al.*, 2010). This is due to increasing anthropogenic emissions of gases which react in the atmosphere to form ozone (Denman *et al.*, 2007), but is also partly due to the increased mixing of stratospheric ozone into the troposphere as a result of climate change (Hegglin and Shepherd, 2009). The key ozone-precursor gases are volatile organic compounds (VOC) and oxides of nitrogen (NO_x). Intercontinenal transport of these precursors is contributing to rising global background ozone concentrations, including in regions where local emissions are decreasing (Dentener *et al.*, 2010).

Negative effects of the current levels of ozone have been widely documented (Mills *et al.*, 2011). A meta-analysis of over 300 articles addressing the effect of ozone on tree growth (Wittig *et al.*, 2009) - largely focussed on northern-hemisphere temperate and boreal species - concluded that current levels of tropospheric ozone are suppressing growth by 7% relative to pre-industrial levels. Modelling studies extrapolating measured dose-response functions suggest a 5 to 30% contemporary reduction in Net Primary Productivity (NPP) worldwide (Sitch *et al.*, 2007) and 1-16% in temperate forests (Ainsworth *et al.*, 2012).

The mechanisms by which ozone affects plant growth are now better known (Hayes *et al.*, 2007; Ainsworth *et al.*, 2012). Chronic exposure to ozone at levels above about 40 ppb generally reduces stomatal conductance and impairs the activity of photosynthetic enzymes (The Royal Society, 2008) although some evidence also suggests ozone exposure may increase stomatal conductance (Wilkinson and Davies, 2010). For the species studied, carbon assimilation rates are generally reduced and respiration increases, leaf area is reduced and leaf senescence accelerated - all leading to a reduction in NPP and biomass accumulation. Gymnosperms are less sensitive than angiosperms. In a modeling study, lower stomatal conductance due to ozone exposure increased river runoff by reducing the loss of soil moisture through transpiration (Huntingford *et al.*, 2011), although studies that measured runoff are contradictory on this issue (Wittig *et al.*, 2007; McLaughlin *et al.*, 2007; Mills *et al.*, 2009; Huntingford *et al.*, 2011).

A modeling study (Sitch *et al.*, 2007) suggests that the negative effects of rising O_3 on plant productivity could offset 17% of the projected increase in global carbon storage due to increasing CO_2 concentrations, but the possible interactive effects between CO_2 and O_3 are poorly understood (The Royal Society, 2008). Reduced stomatal conductance widely observed under elevated CO_2 should help protect plants from ozone damage. Some chamber experiments (Bernacchi *et al.*, 2006) and model studies (Klingberg *et al.*, 2011) suggest this to be the case. The one plot-scale FACE study of CO_2 and O_3 interactions in a temperate forest (Karnosky *et al.*, 2005; Hofmockel *et al.*, 2011) suggests that the effects of O_3 and CO_2 are not independent and may partly compensate for one another.

There is genotypic variation in sensitivity to O_3 (Ainsworth *et al.*, 2012). Other than changing cultivars or species, there is not believed to be much scope for management actions promoting adaptation to higher levels of O_3 (Teixiera *et al.*, 2011; Wilkinson and Davies, 2010). Research into developing ozone resistant varieties and/or chemical protectants against damage may provide management options in the future (Ainsworth *et al.*, 2012, Wilkinson and Davies, 2010).

4.2.4.4. Rising CO_2

The effects of rising CO_2 on the global carbon cycle are discussed in chapter 6 of the WG1 report [Box 6-3, in the SOD]. The discussion here is focused on impacts on terrestrial ecosystems and inland water systems.

Since AR4, investigation of elevated CO_2 effects on plants and ecosystems has focused mainly on Free Air CO_2 Enrichment (FACE) techniques, which have now been in use for approximately 20 years (Leakey *et al.*, 2009) and are considered more realistic than earlier approaches using enclosed chambers because plant community and atmospheric interactions and below-ground conditions are more like those of natural systems. C3 plant species, which includes nearly all tree species, show a general increase in photosynthesis under elevated CO_2, although the response varies between species. Although FACE experiments indicate lower responses of crop yields to elevated

CO_2 than chamber studies, FACE experiments initially suggested greater biomass production of trees (Leakey *et al.*, 2009). But newer results from older stands show that different system respond differently, and only at the Duke forest, a loblolly pine (*Pinus taeda*) stand in North Carolina has biomass accumulation been enhanced several years after canopy closure on rather nutrient poor soils (McCarthy *et al.*, 2010). At most other tree FACE experiments, most of the additional carbon gain has been invested into below-ground pools with short residence time, such as fine roots (Körner *et al.*, 2005; Finzi *et al.*, 2007), and the initial positive response of NPP at the Oak Ridge experiment with sweetgum (*Liquidambar styraciflua*) has disappeared due to progressive nitrogen limitation with stand development (Norby *et al.*, 2010). Acclimation (“down-regulation”) occurs under long-term exposure, leading to cessation of effects in some studies (Norby and Zak, 2011) but with on-going stimulation of photosynthetic carbon assimilation due to elevated CO_2 persists at a level of 19 to 46% for approximately 600 ppm CO_2 relative to 370 ppm reported elsewhere (Leakey *et al.*, 2009). Kongstad *et al.* (2012 did not find such increases for a temperate heathland. Paleo records over the Late Quaternary also indicate effects of CO_2 at the ecosystem scale across the globe (Prentice and Harrison, 2009). Generally, nitrogen use efficiency and dark respiration are also both increased under higher CO_2 (Leakey *et al.*, 2009), but in some tree FACE experiments, productivity increases as a result of enhanced CO_2 were sustained by increased nitrogen uptake rather than increased nitrogen use efficiency (Finzi *et al.*, 2007). Transpiration is decreased due to reduced opening of stomatal apertures which does not acclimate to higher CO_2 in the medium term, *i.e.* the scale of several years leading to greater water use efficiency (Leuzinger and Körner, 2010; Leakey *et al.*, 2009; De Kauwe *et al.*, 2013) – this is corroborated by additional evidence from studies of stable carbon isotopes (Barbosa *et al.*, 2010; Koehler *et al.*, 2010; Silva *et al.*, 2010; Maseyk *et al.*, 2011). C4 plant species, which includes most tropical grasses and some crops, undergo photosynthesis via a different biochemical pathway which is not directly affected by elevated CO_2. However, CO_2 rise generally increases water use efficiency of C4 plants which can exert indirect effects on growth (Leakey *et al.*, 2009). Experiments have also shown that elevated CO_2 has potential to stimulate root growth (e.g. Finzi *et al.*, 2007; McMurtrie *et al.*, 2012), mineralisation of soil organic matter (Drake *et al.*, 2011; Carney *et al.*, 2007, but see Finzi *et al.*, 2007) and soil microbial communities (Carney *et al.*, 2007), although Norby and Zak (2011) suggests that elevated CO_2 effects on the microbial community structure are minor. Impacts of CO_2 physiological forcing may extend beyond the organisms themselves – increased water use efficiency may significantly influence hydrological impacts (see Box CC-VW).

Elevated CO_2 can assist in maintaining resilience of individual species against other stresses, such as high temperature, drought and ozone, as ozone exposure decreases with lower stomatal conductance (Sitch *et al.*, 2007). It is also suggested that faster growth rates under higher CO_2 can allow woody plants to become tall enough to withstand ground fires, and hence alter the fire/vegetation regime in rangelands (Bond and Midgley, 2001; Scheiter and Higgins, 2009) It is also suggested that differential species responses to elevated CO_2 are altering competition (Dawes *et al.*, 2011), for example, increasing the likelihood of faster-growing species such as lianas out-competing slower-growing species such as trees (Potvin *et al.*, 2007; Lewis *et al.*, 2009a).

The interactive effects of elevated CO_2 and other global changes (such as climate change, nitrogen deposition and biodiversity loss) on ecosystem function are extremely complex and as yet poorly predictable (Potvin *et al.*, 2007). For example, in one ten-year temperate grassland experiment in Minnesota, elevated CO_2 halved the loss of species richness due to nitrogen addition (Reich, 2009), whereas no such change was reported for a similar experiment in annual grassland on serpentine soils in California (Zavaleta *et al.*, 2003a) or an alpine grassland in France (Bloor *et al.*, 2010) or a Danish heathland ecosystem (Kongstad *et al.*, 2012). Some of the mechanisms of community and production changes under multi-factor forcing may be mediated through changes in plant litter quality, although in the temperate grassland experiment described above the changes in litter decomposition rates were less marked than the changes in the chemical composition of tissues (Knops *et al.*, 2007). Hyvönen *et al.* (2007) review the combined effects of elevated CO_2, temperature, nitrogen deposition and management on carbon sequestration in temperate and boreal forests and conclude that findings extrapolated from experiments that only consider one of these factors in isolation can be misleading. Since FACE experiments either examine CO_2 effects in isolation, or in conjunction with a very limited set of imposed climate changes such as elevated temperature, the extent to which CO_2 responses are affected by a range of temperature changes or other climatic or environmental factors remains poorly studied. A further, broader analysis supports this, and further suggests that the magnitude of CO_2 effects decreases as the scale of study increases (Leuzinger *et al.*, 2011).

Inclusion of CO_2 effects can be a first-order influence on model projections of ecosystem and hydrological responses to anthropogenic climate change. For example, most CMIP3 climate models project a drying, warming trend in Amazonia, and this leads to widespread forest loss being simulated under most climate projections in a model that ignores CO_2 effects (Salazar *et al.*, 2007). However, when CO_2 effects are included, the same model projects forest loss under fewer climate projections (Lapola *et al.*, 2009). The current generation of dynamic global vegetation models (DGVMs; (Sitch *et al.*, 2008), which includes those used within the CMIP5 Earth System Models, uses formulations based on experimental work that pre-dates FACE experiments (e.g., Farquhar *et al.*, 1980; Collatz *et al.*, 1992). However, the DGVMs simulate present-day global carbon budgets that agree with those inferred from observations such as the atmospheric CO_2 record (Sitch *et al.*, 2008).

The effect of CO_2 on plant physiology independent of its role as a greenhouse gas has implications for the definition of “dangerous climate change” in terms of levels of global mean temperature rise, and for the use of “CO_2 equivalent” metrics for comparing different greenhouse gases. Aside from uncertainties in the response to a given change in CO_2 concentration, the relative importance of radiative forcing and “CO_2 physiological forcing” depend on uncertainties in the response of global climate to radiative forcing and also on the relative proportions of CO_2 and other greenhouse gases (Betts *et al.*, 2012). The impacts of, for example, a 2°C rise in global mean temperature may have a very different net impact on ecosystems depending on the change in CO_2 concentration accompanying this rise. A high climate sensitivity and/or a higher proportion of non-CO_2 GHGs would imply a relatively low CO_2 rise at 2°C global warming, so the offsetting effects of CO_2 fertilization and increased water use efficiency would be smaller than for low climate sensitivity and/or a lower proportion of non-CO_2 GHGs. Similarly, inertia in the climate system means that warming would be expected to continue for many decades after stabilisation of GHG concentrations, so the relative contribution of CO_2 physiological effects would diminish over time. Comparison of the effects of CO_2 with other GHGs in terms of the current radiative forcing-based metrics may therefore not be representative of the relative effects of different GHGs on ecosystems and hydrology (Huntingford *et al.*, 2011).

There remain still important limitations on understanding of CO_2 responses. Large-scale FACE experiments have still only been conducted for up to two locations for any particular ecosystem type, and these are in temperate and boreal regions (e.g. Hickler *et al.*, 2008); there is currently no tropical FACE experiment. The scale of controlled experiments is limited to approximately $100m^2$, and extrapolation to larger scales may not be appropriate as other constraints may be important, for example large-scale atmospheric feedbacks (Körner *et al.*, 2007). Similarly, the limited size of FACE experiments means that influences on catchment-scale hydrology have not yet been studied experimentally. The majority of FACE experiments examine CO_2 concentrations of approximately 550 ppmv), which has been projected to be reached by the end of the 21st Century under a number of scenarios including RCP6.0 (van Vuuren *et al.*, 2011), whereas higher concentrations are projected under higher emissions scenarios; RCP8.5 reaches a CO_2 concentration of approximately 900 ppmv by 2100 (van Vuuren *et al.*, 2011). However, the basic physiology of photosynthesis suggest that CO_2 effects saturate at levels of approx. 700 ppmv (Long *et al.*, 2004). Moreover, FACE experiments impose a sudden increase of CO_2 concentration as opposed to the continuous rise measured in the present-day atmosphere. The extent to which photosynthesis and nitrogen and water use efficiency continue to increase with ongoing CO_2 rise therefore remains poorly-constrained. Overall, there is *medium confidence* (*much evidence, medium agreement*) that increases in CO_2 up to about 600 ppm will continue to enhance photosynthesis and plant water-use efficiency, but at a diminishing rate

4.2.4.5. Diffuse Versus Direct Radiation

The quantity and size distribution of aerosols in the atmosphere alters both the amount of solar radiation reaching the Earth’s surface and its distribution between direct and diffuse radiation. There are observed trends in diffuse and direct radiation in many parts of the world, usually in the direction of overall ‘dimming’. Locally, direct radiation is reduced by up to 30 $W\ m^{-2}$, with an accompanying increase in diffuse radiation of up to 20 $W\ m^{-2}$ (Kvalevåg and Myhre, 2007). The global mean direct and diffuse radiation changes due to aerosols are -3.3 and $+0.9\ W\ m^{-2}$, respectively (Kvalevåg and Myhre, 2007). For a constant total radiation, an increased fraction received as diffuse radiation theoretically increases net photosynthesis, (Knohl and Baldocchi, 2008; Kanniah *et al.*, 2012) and potentially could alter the hydrological balance and soil temperature. In a global model which included this process, an increase in diffuse fraction of solar radiation due to volcanic and anthropogenic aerosols and cloud cover was simulated to lead to approximately a 25% increase in the strength of the global land carbon sink between 1960 and 1999; but under a scenario of climate change and decreased anthropogenic aerosol concentration, this enhancement declined to near zero by the end of the 21st Century (Mercado *et al.*, 2009). The influence of form of radiation on plant growth and the land carbon budget is a potentially important unintended consequence of solar radiation management schemes that involve the injection of aerosols into the stratosphere to reduce radiant forcing (Boucher *et al.*, in preparation) but is presently insufficiently researched for adequate assessment.

4.2.4.6. Invasive and Alien Species

Since the IPCC AR4, the number of observations of the spread and establishment of alien species attributed to climate change has increased for several taxa (e.g. Walther *et al.*, 2009) and for particular areas, including mountain tops and polar regions (McDougall *et al.*, 2011; Chown *et al.*, 2012). The aggressive expansion of plant and animal species beyond their historical range is having increasingly negative impacts on ecosystem services and biodiversity (*high confidence*; Brook, 2008; Burton *et al.*, 2010; McGeoch *et al.*, 2010; Simberloff *et al.*, 2013). Climate change will exacerbate some invasion impacts and ameliorate others (Peterson *et al.*, 2008; Bradley *et al.*, 2009; Britton *et al.*, 2010). The spread of alien species has several causes, including habitats made favorable by climate change (Walther *et al.*, 2009), deliberate species transfer and accidental transfer due to increased global movement of goods.

In most cases climate change increases the likelihood of the establishment, growth, spread and survival of invasive species populations (Dukes *et al.*, 2009; Walther *et al.*, 2009; Bradley *et al.*, 2010; Huang *et al.*, 2011; Chown *et al.*, 2012). However, divergent alien species responses and local consequences are expected (e.g. Rahel and Olden, 2008; Frelich *et al.*, 2012; Haider *et al.*, 2012; West *et al.*, 2012). Invasive species compared to native species might have traits that favor their survival, reproduction and adaptation under changing climates; invasive plants in particular tend to have faster growth rates and are particularly favored when resources are not limited (*medium to high confidence*; Buswell *et al.*, 2011; Davidson *et al.*, 2011; Zerebecki and Sorte, 2011; van Kleunen *et al.*, 2010; Willis *et al.*, 2010a; Haider *et al.*, 2012; Matzek, 2012). Invasive plants tend to be more drought tolerant (Crous *et al.*, 2012; Matzek, 2012; Perry *et al.*, 2012), and on average have higher overall metabolic rates, foliar nitrogen concentrations and photosynthetic rates than their native counterparts (Leishman *et al.*, 2007).

Extreme climate events may provide opportunities for invasion by generating disturbances and resource pulses (Diez *et al.*, 2012). Current warming has already enabled many alien species, including plant, vertebrate, invertebrate and single cell taxa, to extend their distributions into new areas (*high confidence* for plants and insects; Walther *et al.*, 2009; Smith *et al.*, 2012). Population declines and range contractions are however predicted for some invasive species in parts of their ranges (Bradley *et al.*, 2009; Bertelsmeier *et al.*, 2012; Sobek-Swant *et al.*, 2012; Taylor *et al.*, 2012;). The expansion of invasive species in some areas and contraction in others will contribute to community re-organisation and the formation of novel ecosystems and interactions in both terrestrial and freshwater habitats (*high confidence*; e.g., Kiesecker, 2011; Britton *et al.*, 2010; Martinez, 2012; see also chapter 4.3.2.5.). For example, invasive grasses will probably be favored over native ones with increasing temperatures (Parker-Allie *et al.*, 2009; Chuine *et al.*, 2012; Sandel and Dangremond, 2012).

Benefits to biodiversity and society as a result of interactive effects of climate change and invasive species will be experienced in individual cases, such as increases in resources available to some threatened species (Caldow *et al.*, 2007), forest structural recovery (Bolte and Degen, 2010) and available biomass for timber and fuel (van Wilgen and Richardson, 2012). The effect of invasions on net changes in carbon stocks are situation specific, and may be either positive or negative (Williams *et al.*, 2007a). Rising CO_2 levels will increase the growth rates of most invasive plant species (Mainka and Howard, 2010), but the effectiveness of invasive species management for sequestering carbon is uncertain and context specific (Peltzer *et al.*, 2010). Longer term, indirect effects of invasive species will be more important than direct, short-term effects, as a result of changes in soil carbon stocks and tree community composition (*low-medium confidence*; Peltzer *et al.*, 2010).

Threat syndromes are formed by synergistic interactions between climate change and invasive species, along with landscape change, habitat disturbance and human-facilitated breakdown of dispersal barriers (Brook, 2008; Angeler and Goedkoop, 2010; Bradley *et al.*, 2010; Winder *et al.*, 2011; Cahill *et al.*, 2013). Climate change and invasive species change the risk and properties of fire, and the interaction is being reported more frequently as a direct result of higher temperatures and increased invasive plant biomass (*high confidence*; Abatzoglou and Kolden, 2011). In freshwater systems, alien species establishment and survival, species interactions and disease virulence will change as a result of changes in frequency of high-flow events, increasing water temperature, water properties and water demand (*medium confidence*; Schnitzler *et al.*, 2007; Rahel and Olden, 2008; Britton *et al.*, 2010).

A range of climate change-related variables (extreme events, changes in precipitation, temperature and CO_2) will continue to exacerbate the establishment and spread of pests, vectors and pathogens and negatively impact on crop production (*medium confidence*; Robinet and Roques, 2010; Clements and Ditommaso, 2011). Warming has led to the spread of many invasive insect species such as the mountain pine bark beetle and resulted in forest destruction (*high confidence*; Kurz *et al.*, 2008). The interactions between crop growth, climate change and pest dynamics are however complex to predict (West *et al.*, 2012). Management strategies may become less effective as a consequence of decoupling of biocontrol relationships and less effective mechanical control as biomass of invasive species increases (*low to medium confidence*; Hellmann *et al.*, 2008).

4.3. Vulnerability of Terrestrial and Freshwater Ecosystems to Climate Changes

Vulnerability of terrestrial ecosystems to climate change is defined as the combination of three things: the degree to which their climatic environment changes relative to conditions under which the ecosystem evolved; the sensitivity of ecosystem processes to the elements of climate undergoing change; and the degree to which the system (including its coupled social elements) can maintain its structure, composition and function in the presence of such change, either by tolerating the change or adapting to it. See WGII chapter 19 for a fuller discussion on vulnerability concepts.

4.3.1. The Importance of Changes in Disturbance Regime

The species composition at a given location is determined by three factors: the physiological tolerance of the various species that have access to the site in relation to the range of conditions experienced there; interactions with other species, including competitors, symbionts, predators, prey and pathogens; and the ability of species to reach the location in evolutionary or recent times. Occasional disturbances that relieve competition and create opportunities for establishment and success of less-dominant species are important in maintaining diversity. The average environmental conditions are often less of a determinant of species ranges than the extremes, such as the occurrence of exceptionally cold or hot days or droughts exceeding a certain duration, which are often defined as ‘disturbances’. The change in probability of such extremes is typically disproportionately larger than the change in the mean (see IPCC, 2012, but also Diffenbaugh *et al.*, 2005). Fire, floods and strong winds are all examples of biodiversity-sustaining events, provided that their frequency and intensity does not deviate greatly from the regime that prevailed at the location in evolutionary time; outside this range they have adapted to (Connell, 1978).

It is thought that widespread compositional shifts resulting from climate change in interaction with other factors will often be associated with changes in the disturbance regime, rather than physiological tolerance (Thonicke *et al.*, 2008). A ‘disturbance regime’ refers to the totality of different types of disturbance events in a system, each characterized by their probability-intensity function and other relevant attributes, such as their seasonal distribution. A corollary is that disturbance-related change is likely to abrupt rather than gradual.

Change in the fire disturbance regime, in particular, is emerging as a key, mechanism of terrestrial ecosystem change and an early indicator of change that has been detected and in some cases attributed to climate change (Westerling *et al.*, 2006; Littell *et al.*, 2009; Westerling *et al.*, 2011; Moritz *et al.*, 2012).

4.3.2. Evidence of Change in Ecosystems

This section highlights key indices of change in terrestrial and freshwater ecosystems over the recent past. It assesses the degree of confidence that change can be detected and the extent to which changes can be attributed to changes in climate (Figure 4-5). Confidence in detection of change is considered to be very high when there is high agreement between many independent studies, species, ecosystems or regions and where there is robust evidence that the changes over time are statistically significant (see WGII, Chapter 18; Mastrandrea *et al.*, 2010). Note that a slightly different definition than Chapter 18 for detection is used, because detection here is based solely on the presence of a temporal trend and does not attempt to distinguish natural from climate related variation. Confidence in attribution to climate change is very high when three criteria are satisfied: changes correspond to a sound mechanistic understanding of responses to climate change; time series of observations are sufficiently long to detect trends correlated with climate change; and confounding factors can be accounted for or are of limited importance. We have provided estimated levels of confidence even in cases where the capacity for detection or attribution capacity is low or very low, because changes in these ecosystem properties or processes could have large impacts on biodiversity or ecosystem services at regional to global scales. It is also important to account for the spatial distribution of climate change trends: for example, warming trends are very high in the Arctic and small or negative in parts of South America (Burrows *et al.*, 2011). Statements of confidence for detection and attribution are given without references, as detailed traceability is provided in the section 4.3.2, which follows this introduction.

Some of the subsections referred to include assessments of model-based projections of future change, but this analysis of detection and attribution does not cover projected changes in ecosystems. The absence of observed changes does not preclude high levels of confidence in projections of change in the future because 21st century climate change is projected to substantially exceed changes experienced over the last century, and because ecosystem responses to climate change may be non-linear and may appear after considerable time lags.

[INSERT FIGURE 4-5 HERE
Figure 4-5: Confidence in detection of change and attribution of observed responses of terrestrial ecosystems to climate change. Confidence levels have are based on expert judgment of the available literature following the IPCC uncertainty guidance (Mastrandrea *et al.*, 2010), and detection and attribution criteria outlined in Chapter 18. The points in the figure represent global and cross-taxon assessments; the positioning may be different for specific taxa or regions.]

Phenology (see 4.3.2.1) - Since the AR4 report there has been a significant increase in the spatial, temporal and taxonomic coverage through ground-based phenological observation networks, data mining and remote sensing. These observations show that phenology, i.e., the timing of key life history events such as flowering in plants or nesting for birds, has shifted for many but not all species over the last several decades (*high confidence* due to *robust evidence* but only *moderate agreement* when examined across all species). Attribution of temporal shifts in phenology to qualitative expectations of responses due to global warming has given way to more refined analyses and models that account for regional differences in warming trends, urban heat island effects, confounding effects of other global change drivers, and non-linear responses of phenology to warming. These advances notwithstanding, attribution can only be made with *high confidence* because there are a wide range of confounding factors, a substantial fraction of species that have not responded in a predictable manner and discrepancies between phenological shifts in experiments vs. observations.

Primary Productivity (see 4.3.2.2) and Biomass and C Stocks (see 4.3.2.3) - Evidence has accumulated from a wide range of sources including eddy flux towers, inversion of atmospheric CO_2 concentrations, remote sensing and models that, once the effects of deforestation are accounted for, terrestrial ecosystems are currently net sinks for carbon over much of the Northern hemisphere and parts of the Southern hemisphere (*high confidence*). Measurements of increased tree growth over the last several decades, a large sink for carbon, are consistent with this but confounding factors such as N deposition, afforestation and land management make attribution of these trends to climate change difficult (*low confidence*). Most studies speculate that rising CO_2 concentrations are contributing to this trend through stimulation of photosynthesis, but there is no clear, consistent signal of a climate change contribution.

Evapotranspiration (see 4.3.2.4) - Evapotranspiration is now being monitored at a variety of scales ranging from individual plants to large regions. A variety of studies suggest that evapotranspiration increased over the period 1970-1990, but there is substantial uncertainty in this estimate due to low agreement across studies leading to *low confidence* in detection of a trend. The trend of rising evapotranspiration from 1970-1990 has been attributed to global warming, and the absence of a continued trend in from the 1990s onward has been attributed to increased water stress. However, there is *low confidence* in these attributions because of the large number of confounding factors that influence transpiration including N deposition, land management and irrigation.

Species Distributions (see 4.3.2.5) - Depending on the species and species group, there are varying degrees of confidence in the detection of species range shifts and that these range shifts can be attributed to climate change. The number of species studied has considerably increased since the AR4 report as have the number of studies examining the mechanisms underlying range shifts. There is a wide range of evidence from models, field studies, and quantitative comparisons between observed and expected range shifts that some species and species groups, especially arthropods, have shifted their ranges significant distances (10s of km or more) over the last several decades (*high confidence*). Range shifts — that must be distinguished from shifts in community composition — in other key species groups such as plants have been much more difficult to detect, meaning there is only *medium confidence* in detection in range shifts when examined across all species groups. Range shifts in some species groups, e.g., arthropods, correlate well with warming over the last several decades and can be linked to changes in climate through understanding of mechanisms. But for many other species groups range shifts are more difficult to attribute to changes in climate because the climate signal is small, there are many confounding factors, differences between expected and observed range shifts are large, or variability within or between studies is high. Thus there is only *medium confidence* in attribution when examined across all species. An importance advance since the AR4 report is the recognition changes in climate over the last several decades have led to range shifts that are frequently not towards the poles or up in altitude due to many factors including interactions between warming, land use and changes in precipitation (*high confidence*).

Global Species Extinctions (see 4.3.2.5) - There is *high confidence* that global species extinctions are at or above the highest rates of species extinction in the fossil record, and *high confidence* that global extinctions have increased in some species groups, e.g., amphibians, over the last several decades. However, across all taxa there is only *low confidence* that rates of species extinctions have increased over the last several decades. Only a small fraction of observed species extinctions have been attributed to climate change — most have been ascribed to invasive species, overexploitation, habitat loss or habitat modification. As such, there is *very low confidence* that observed species extinctions can be attributed to recent climate warming given the small fraction of species for which global extinction has been ascribed to climate change and tenuous nature of most attributions. However, in the specific case of Central American amphibians, there is *medium evidence* that recent climate warming has contributed to extinctions and *medium confidence* in this attribution. There is *low agreement* among investigators concerning the importance of climate compared to other factors such as invasive disease and habitat loss.

Invasive and Alien Species (see 4.2.4.6) - There is *very high confidence* that species invasions are increasing over the last several decades. There is *high confidence* that recent climate trends have contributed to the establishment, growth, spread and survival of some alien species populations in some regions, but only *low confidence* that the species invasions have generally been assisted by recent climatic trends because of the overwhelming importance of human facilitated dispersal in mediating invasions.

Tree Mortality (see 4.3.3.1, Box 4-2) - Extensive tree mortality appears to be increasing globally, but there is *low confidence* in detection due to a lack of temporal and spatial coverage of tree mortality. In particular, the increase in reporting of mortality may reflect greater observation effort rather than a real increase in mortality. In many cases, tree mortality can clearly be linked directly to climate impacts, especially heat and drought. However, attribution to directional climate change over the last several decades is difficult (*low confidence*) due to lack of time series measurements for a large range of forested systems and the large number of confounding factors mediating tree mortality.

Boreal Forest Regime Shift (see 4.3.3.1.1, Box 4-4) - An increase in tree mortality is observed in many boreal forests, with particularly widespread dieback related to insect infestations in North America. Tree health in boreal forests varies greatly among regions, which coupled with insufficient temporal coverage means that there is *low confidence* in the detection of a clear temporal trend in morality at the global scale. Models and paleobotanical data indicate that regression of boreal forest at its southern edge is a predictable response to warming. High magnitudes of climate change over most of boreal forest also facilitate attribution to global warming. In some cases, tree mortality can be linked directly or indirectly (e.g., due to changes in insect and pathogen ranges) to fluctuations in climate. However, the lack of long-term data sets and high spatial heterogeneity means that attribution to climate change is of *low confidence*.

Amazon Forest Regime Shift (see 4.3.3.1.3, Box 4-3) - Long-term increases in tree turnover (increased mortality and growth) in the humid tropical forests of the Amazon basin have been documented with *moderate confidence*. In addition, two episodes of extreme drought over the last decade have led to increased mortality of large trees. There is *low confidence* that this represents a trend towards degradation of humid tropical forest, since structural changes in intact forests have been minor. Observed changes in tree turnover have been ascribed to a variety of mechanisms including rising CO_2 effects on vines, recovery from past disturbance and changing climate: the attribution to these various drivers is difficult due to limited temporal and spatial coverage. Models and experiments lend credence to a contribution of climate to increased tree mortality and growth. There is *very low confidence* in attribution of observations to climate change because of the short period of intensive monitoring records and because warming trends over the last several decades are weak in this region.

Tundra Regime Shift (see 4.3.3.4) - Field and satellite measurements indicate an increase in shrub growth and permafrost thawing in many areas of the Arctic tundra. Lack of temporal coverage makes it difficult to know if this is a strong directional signal leading to *medium confidence* in detection of a trend. It is not clear to what extent this presages boreal forest encroachment into tundra, which would have much larger impacts on ecosystem structure and function. Experiments, models and paleontological responses of tundra to past warming all indicate that the increase in shrub coverage and permafrost thawing are predictable responses to climate warming trends. High magnitudes of climate change over the last 50 years for most of the Arctic facilitate attribution. The lack of long-term monitoring data makes it difficult to attribute these changes to climate change with greater than *medium confidence*.

Cultural Landscapes (see 4.3.3.5) - There is *very high confidence* that species composition and landscape structure are changing in cultural landscapes such as Satoyama landscapes in Japan or mixed forest, agricultural landscapes in Europe. Models and experiments suggest that climate change should be contributing to these observed changes. The land use and land management signal is so strong in these landscapes, that there is *very low confidence* that we can attribute these observations to climate change.

Evolutionary and Genetic Adaptation (see 4.4.1.2) - While there are an increasing number of observations of "rapid evolutionary" responses to climate variation, the number of species studied is extremely limited. In addition, it remains difficult to separate phenotypic from genotypic adaptation meaning that there is only *low confidence* that we are detecting a widespread signal of evolutionary or genetic adaptation to climate. An increasing number of models and experiments illustrate that "rapid evolutionary" responses are possible and even probable response to climate change. In a few cases, strong correlations between climate trends and changes in gene frequencies underlying phenological responses to climate trends suggest that climate change is an important driver of rapid evolution. The limited number of well-studied cases means there is only *low confidence* in attribution of adaptation as a generalized response to changes in climate over the last several decades.

4.3.2.1. Phenology

A large number of site-specific studies, and more recently satellite imagery, allow monitoring of phenology. The advance in spring events (e.g. breeding, bud burst, breaking hibernation, flowering, migrating,) has been reported for many regions, especially from the northern hemisphere but fewer in the southern hemisphere and for many plant and animal taxa. Since the AR4 many new studies showing phenological adaptations of species as response to climate change (e.g., amphibians: Kusano and Inoue, 2008; birds: Pulido, 2007; Thorup *et al.*, 2007; mammals: Adamik and Kral, 2008; Lane *et al.*, 2012; plants: Cleland *et al.*, 2007; Gordo and Sanz, 2009; plants and animal taxa: Høye *et al.*, 2007; Primack *et al.*, 2009) and meta analyses were published (observed data: Parmesan, 2006; Parmesan, 2007;

Thackeray *et al.*, 2010; Cook *et al.*, 2012; Ma and Zhou, 2012; Wolkovich *et al.*, 2012; experimental warming experiments: Musolin *et al.*, 2010; Cleland *et al.*, 2012).

Large-scale changes and variations in vegetation have been monitored by satellite since 1982 (White *et al.*, 2009). The Advanced Very High Resolution Radiometer (AVHRR) quantifies the differences in visible and near-infrared wavebands of outgoing radiation (NDVI) which is related to the quantity of photosynthetically-active vegetation. The times of maximum and minimum rate of change of NDVI provide a metric of the growing season. From 1982 to 2008 the NDVI-defined start of the growing season advanced by 5.4 days at the hemispheric scale, and the end was delayed by 6.6 days (Jeong *et al.*, 2011). Rates of change varied over time and at smaller scales. Changes were found to be strongly related to temperature trends, although changes in precipitation may also be key drivers, especially in more arid regions (McPherson, 2007). Studies with the more recent instrument, Moderate Resolution Imaging Spectrometer (MODIS), and other metrics such as Leaf Area Index (the ratio of leaf area to ground area; Ahl *et al.*, 2006) provide a similar picture at large scales, although results can differ at local scales due to the use of different instruments, indices and trend detection methods. The relatively short duration of satellite observations makes trend detection particularly sensitive to the choice of analysis period. Nevertheless, the general emerging picture of an advancement of the start of the growing season length is consistent with ground-based phenology studies. At a regional scale, a combination of species-level observations, meta-analysis, NDVI measurements and phenology modeling to reveal geographically different advancements in spring phenology of Chinese plant communities in different Ecoregions and Biomes between the 1960s and 2000s (Ma and Zhou, 2012).

Changes in breeding phenology are reported from various regions and different taxa (insects, birds, mammals, amphibians; e.g. Parmesan, 2006; Parmesan, 2007; Post *et al.*, 2008; Primack *et al.*, 2009). Various factors can be attributed to changes on breeding phenology, e.g. food availability, increasing spring temperatures. In the northern hemisphere several studies show advancements of egg laying dates in birds (e.g. Parmesan, 2007: -3.70 days/decade ± 0.7, n= 41 species in a meta-analysis). In mammals, Réale *et al.* (2003) found for the female North American squirrel (*Tamiascurus hudsonicus*) an advancement of 18 days of the mean parturition day in 10 years (1992-2002) in the Yukon area, Canada, coinciding with increasing abundance of white spruce cones, the major food source. For the southern hemisphere the opposite pattern, a significant delay of the mean breeding date by 2.8 to 3.7 days between 1950 and 2004 for two of nine seabirds in the Eastern Antarctic (Barbraud and Weimerskirch, 2006).

Patterns of changes in autumn migration in birds are mostly not consistent (delayed, advanced, no change) across analyzed species and regions and appear to be highly related to non-climatic variables (e.g. Sokolov, 2006; Adamik and Pietruszkova, 2008). Phenological response can differ with migration strategy in birds, such as short distant migrants show greater advancements in spring arrivals than long distant migrants (e.g. Saino *et al.*, 2009; but see Parmesan, 2006 for different patterns). Insects show also a variety of phenological responses to changing temperatures (e.g. reviewed in Robinet and Roques, 2010). Development rates speed up and for polyvoltine species an increase in number of generations attributed to increasing temperatures and a lengthening of the growing seasons due to earlier timing of last winter frost and later timing of first fall frosts) are reported (e.g. Menzel *et al.*, 2003; Kunkel *et al.*, 2004; Sunley *et al.*, 2006; Robinet and Roques, 2010)

A variety of environmental drivers could affect behavioral changes in species. Experimental-manipulation shows that higher temperatures lead to significantly earlier egg laying dates of the great tit (*Parus major*) in 5 out of 6 years (Visser *et al.*, 2009), but rates of seasonal warming may also be important (Schaper *et al.*, 2012). In a temperate region (Massachusetts, USA), declining sizes of migration cohorts or of populations appeared to account for a large amount of the variation in previously documented changes in migration times between 1970 and2002 (Miller-Rushing *et al.*, 2008). After accounting for changes in migration cohort size, migration distance, climatic variables, and migration date explained portions of the variation in migratory changes over time. Changes in migration phenology cannot only be attributed to changes in temperature changes but also to differing variability of changed feathers during moulting times, food availability at stop-over places and differing health conditions of individual species (Gordo, 2007).

Snow cover and snow depth can also be important factors. Interactions between temperature precipitation determining snowmelt changes, which is reported to lead to earlier flowering and appearances of plants and arthropods in Greenland between 1996 and 2005 (Høye *et al.*, 2007) and earlier flowering in an alpine plant in the

Rocky Mountains, USA between 1975 and 2008 (Lambert *et al.*, 2010; Hülber *et al.*, 2010). Earlier snow melts are reported to decrease floral resources and can hence affect survival of dependent insects in mountain ranges in the USA across 1980, 1985, 1986 and 1989 (Boggs and Inouye, 2012). Mammals show also changes in phenology as effects of climate change induced changes on snowmelt pattern, especially hibernating species, ranging from advancements of emergence dates from hibernation (Ozgul *et al.*, 2010) due to earlier snowmelts or to delayed emergence dates (Lane *et al.*, 2012) due to delayed snowmelts. Delayed emergence from hibernation was also associated with decreased population growth rate (Lane *et al.*, 2012).

Experiments are an important source of information on physiological and phenological responses to changing climate, but some caution should be exercised when translating their results into future projections using models. Wolkovich *et al.* (2012), in a large meta-analysis, suggested that warming experiments substantially underpredict advances in the timing of flowering and leafing of plants. They also showed that experimentally-derived temperature sensitivities of species did not match the observations in the wild. However, in contrast, Gunderson *et al.* (2012) found good agreement between experimental warming and *in situ* observations. Experiments on wild species may also directly affect results; for example, flipper-tagging of penguins can alter their migratory behavior (Saraux *et al.*, 2011).

Generally, there is a great interspecific variability in phenological responses to changing climatic factors (e.g.: Gunderson *et al.*, 2012). Changes in interspecific interactions, such as predator-prey or interspecific competition for food, stemming from changes in phenological characteristics and breakdown in synchrony between species have been observed. Parmesan (2007) found taxonomic groups to be advancing at significantly different rates, with amphibian breeding date advancing by eight times as much as other groups, birds and butterflies were not significantly different from each other, but both showed spring advancement three times stronger than for herbs and grasses. Since most butterfly species eat herbs and grasses as host plants, this suggests an increasing asynchrony between these two interacting groups. Thackeray *et al.* (2010) draw similar conclusions. Species unable to adjust their behavior, i.e. advancement of spring events to keep track with changing climates could be negatively affected. This may be particularly important in highly seasonal habitats (Both *et al.*, 2010). The degree, direction and strength of the asynchrony due to changing climatic variables depends on differences in the phenology of the interacting species (van Asch and Visser, 2007). Increasing temperatures may either bring species more into synch or more out of synch, depending on their respective starting positions (Singer and Parmesan, 2010), although evidence is more towards a loss of synchrony (Visser and Both, 2005). Changes in (a)synchrony of interacting species is assumed to effect dynamical features of ecological communities such as trophic cascades, competitive hierarchies, and species coexistence (Nakazawa and Doi, 2012). Ahola *et al.* (2007) could show that the competition between the resident *P. major* and the migratory pied flycatcher (*Ficedula hypoleuca*) is increasing when the onset of breeding of both is becoming closer to each other and the abundances of both species are increasing (data: 1953–2005; South-Western Finland). This pattern resulted in a relative host change to more long-distant hosts. van Asch and Visser (2007) report increasing asynchrony of the winter moth (*Operophtera brumata*) and its feeding host oak tree (*Quercus robur*) due to increasing spring temperatures and not changing winter temperatures (based on a descriptive model, oak data: 1975-1999, Netherlands, moth data: 1995-1999; Oosterhout, Warnsborn, Doorwerth, Arnhem; Netherlands). The edible dormouse (*Glis glis*), a nest predator advanced its hibernation termination significantly with -8 days per decade in the Czech Republic between 1975-2005 due to increasing annual spring air temperatures, leading to increased nest predation in three out of four bird surveyed species (Adamik and Kral, 2008)

Cross taxa observations show high variation in species- and location specific responses to increasing temperatures in both direction and magnitude (e.g. Parmesan, 2007; Primack *et al.*, 2009; Thackeray *et al.*, 2010). Uncertainties and biases can be introduced in research that compares different taxonomic groups or geographic regions by often incomplete or non-overlapping time series, averaged geographical scales, lack of consideration of effects of local climatic variability (e.g. wind speed, climatic conditions at stop-over places) and mostly unknown pressures in winter ranges for migratory species (Hudson and Keatley, 2010). With too short time series long term trends in phenological changes cannot be detected, although responses to annual climate variability can often be characterized. However, some studies now extend over several decades (Cook *et al.*, 2008) or even 100 years (Naef-Daenzer *et al.*, 2012)**.** Given the geographical coverage and length over time over which studies are now available, there is high confidence (*robust* evidence, high agreement) that phenological shifts are occurring as a response to a warming climate.

4.3.2.2. Primary Productivity

Primary production is the process of plant growth that underpins energy flow through all ecosystems, enabling provisioning services such as crop, forest, livestock and fisheries harvest. It is also fundamental to the regulation of global carbon cycle (see 4.3.2.3. below). Trends in the amount, seasonal timing, variability, location and type of primary production are therefore important indicators of ecosystem function. Well-established theory, experimentation and observation all agree that primary production is directly and indirectly sensitive to almost all aspects of climate change as well as to many of the other changes simultaneously taking place in the world, such as the factors described in section 4.2.4. The complexity of the interactions between driving factors and the frequently non-linear form of the responses to them means that at a given location the net outcome can be an increase in productivity, no change or a decrease.

At continental-to-global scale two main sources of information on primary productivity are available. The first is precise and frequent measurements of atmospheric carbon dioxide, which once the known signal of fossil fuel emissions is removed, show clear patterns in space and time largely related to the primary productivity of the land and oceans. The relative contribution by the land, which consists of a sink term due to increased net productivity plus a source term due to land-use change, can be estimated using isotope measurements, emission databases and models (Canadell *et al.*, 2007). During the decade 2000 to 2009, land net primary productivity at the global scale continued to be enhanced about 5% relative to the postulated pre-industrial level, leading to a land sink of 2.6 ± 0.7 PgC/y (see WG1 chapter 6; Raupach *et al.*, 2008; Le Quere *et al.*, 2009). This net uptake of carbon by the land is highly variable year-to-year, in response to global climate models such as ENSO and major volcanic eruptions (Peylin *et al.*, 2005; Sitch *et al.*, 2008; Mercado *et al.*, 2009). It is currently not possible to state with any degree of confidence that the net uptake of carbon on land has either increased or decreased over the past two decades (Raupach *et al.*, 2008).

It is possible to estimate the net uptake on land at subglobal scales, using inversion modelling techniques and the growing network of precision atmospheric observations. There is broad agreement that the net land uptake in largely-untransformed terrestrial ecosystems is globally distributed, almost equally between forested and non-forested ecosystems, but is offset in the tropics by a large carbon emission flux resulting from land-use change, principally deforestation (Pan *et al.*, 2011).

Space-based remote sensing can in principle monitor trends in vegetation cover and leaf area, from which primary productivity can be inferred. A commonly-used metric is the Normalised Difference Vegetation Index (NDVI), for which over 30 years of observations are available, covering most of the global land surface. The observed trends are discussed under the various ecosystem-specific discussions below. In some cases the trends are sufficiently strong and consistent to support a confident statement about the underlying phenomenon, but in many cases they are not. This may mean that no change has occurred, but simply reflect inadequacies in the indicator, method of analysis and length of the record. The AR4 reported a trend of increasing seasonally-accumulated NDVI (“greening”) at high northern latitudes (Fischlin *et al.*, 2007; based on Sitch *et al.*, 2007), but later observations show a lower rate and no geographical uniformity (Goetz *et al.*, 2007). More than 25% of North American forest areas, excluding areas recently disturbed by fire, showed a decline in greenness and no systematic change in growing season length, particularly after 2000. NDVI trend analysis studies in rangelands show varying patterns around the world, with substantial areas of disagreement between studies (Millennium Ecosystem Assessment, 2005b; Bai *et al.*, 2008; Beck *et al.*, 2011a; Fensholt *et al.*, 2012). There is agreement that the Sahel showed widespread NDVI increase between the mid 1980s and about 2000, along with an increase in rainfall, but no consensus on whether the detected signal represents increased productivity by grasses, trees or forbs; and to what degree it reveals land management efforts or responses to climate (Anyamba and Tucker, 2005; Hickler *et al.*, 2005; Prince *et al.*, 2007; Hellden and Tottrup, 2008; Seaquist *et al.*, 2009). In the period 2000 to 2009 no NDVI trend was apparent in the Sahel (Samanta *et al.*, 2011).

Tree rings record changes in tree growth over approximately the past millennium. Ring width and the wood density within a ring indicate tree productivity during the period represented by the ring. Isotopes within the ring reveal changes in the environment to which the tree was exposed. Variations in tree ring parameters arise from many factors, including temperature, moisture stress, CO_2 fertilization and ozone damage. The most recent rings in most published tree ring chronologies date from before the 1990s (Gedalof and Berg, 2010) so tree ring-based conclusions for more recent dates are based on a smaller body of evidence. Sites which are not sensitive to environmental changes may therefore be under-represented. Direct repeated measurements of tree girth increment in forest monitoring plots (discussed in 4.3.2.3) are an alternate data source for recent decades. Tree ring studies may not be representative of forests in general, as most studies were specifically designed to examine growth in response to environmental changes (Gedalof and Berg, 2010).

Many tree ring records show a tendency of accelerated tree growth during much of the 20th century (Briffa *et al.*, 2008), which often correlates with rising temperature. Direct CO_2 effects, inferred from the ring record once the effects of drought and temperature have been accounted for, have been proposed for approximately 20% of the sites in the International Tree Ring Data Base (Gedalof and Berg, 2010) and studied in detail at some sites (Koutavas, 2008). Since the 1980s a number of tree ring records show a decline in tree growth (Wilson *et al.*, 2007). Several possible causes have been suggested for this, including increasing water stress and ozone damage.

4.3.2.3. Biomass and Carbon Stocks

Forests are routinely monitored for management and research purposes, typically by recording species composition and stem size distribution in hundreds of small plots. Forest carbon stock can be estimated from this and forest area data, usually derived from remote sensing. Repeated forest inventories in principle allow the growth rate and change in carbon stock to be estimated. Forest inventories were designed to track timber volumes; inferring total biomass and ecosystem carbon stocks requires further information and assumptions, which make absolute values less certain, but have a lesser effect on trend detection. Forest inventory systems are well-developed for northern hemisphere temperate and boreal forest (Nabuurs *et al.*, 2010; Ryan *et al.*, 2010; Wang *et al.*, 2010a). Data for tropical and southern hemisphere forests and woodlands also exist (Maniatis *et al.*, 2011; Tomppo *et al.*, 2010) but are typically less available and comprehensive (Romijn *et al.*, 2012). More and better data may become available due to advances in remote sensing (e.g. Baccini *et al.*, 2012) and the REDD+ initiative.

Forests have increased in biomass and carbon stocks over the past half century in Europe (Ciais *et al.*, 2008; Luyssaert *et al.*, 2010) and the USA (Birdsey *et al.*, 2006). Canadian managed forests increased in biomass only slightly over 1990-2008, due to fires and beetle outbreaks (Stinson *et al.*, 2011). Several dozen sites across the moist tropics have been monitored to estimate forest biomass changes. In the Amazon (Malhi *et al.*, 2009a; Phillips *et al.*, 2009) forest biomass has generally increased in recent decades, dropping after a drought in 2005. Globally, mature forests are withdrawing from the atmosphere one fourth of human CO_2 emissions while regrowth forests withdraw an additional 17%. This global terrestrial sink is offset by the losses of forest carbon to the atmosphere through tropical deforestation and land-use (Pan *et al.*, 2011).

The carbon stock in global soils, including litter, peatlands and permafrost, is estimated to be in the order of 3300 PgC (Davidson *et al.*, 2011), which is about ten times more than is contained in forest biomass (Kindermann *et al.*, 2008). The size of this stock represents the balance of inputs from primary productivity and soil respiration. Soil respiration increases with increasing temperature, but the sensitivity remains uncertain (Davidson and Janssens, 2006). An analysis of long-term soil respiration measurements from around the world suggests that soil respiration has increased over the past two decades by an amount of 0.1PgC/y, some of which may be due to increased productivity (Bond-Lamberty and Thomson, 2010). Flooded coastal soils also show increases in respiration, larger than increases in production (Kirwan and Blum, 2011).

4.3.2.4. Evapotranspiration and its Role in the Terrestrial Water Cycle

Transpiration is affected by multiple factors (Luo *et al.*, 2008) including temperature, humidity, soil moisture, solar radiation and CO_2 concentration. Total evapotranspiration (ET: transpiration through plant stomata plus evaporation from the ground surface and leaf surfaces) is monitored with flux towers, but since most records are at most 15 years duration (FLUXNET, 2012) there is insufficient data to calculate large-scale, long-term trends. ET can also be estimated from meteorological observations using the Penman-Monteith equation (Monteith, 1965; Penman, 1948) or simulated with models constrained by observations. Estimates of ET from 1120 globally distributed stations indicate that global land mean ET increased by approximately 2.2% between 1982 and 2002, a rate of increase of 0.5 mm yr^{-2} (Wang *et al.*, 2010b), while other studies using constrained models in combination with other methods indicated trends of between 0.25 mm yr^{-2} to 1.1 mm yr^{-2} during the 1980s and 1990s but with a plateau or even decline since approximately 2000, attributed to reduced net radiation (Vinukollu *et al.*, 2011; Zeng *et al.*, 2012). A multi-model study using a data-driven empirical model and process-based land models (Jung *et al.*, 2010) also suggests that global evapotranspiration rose from the 1980s to the late 1990s but this trend then ceased, with increasing soil moisture limitations being cited as the cause.

Experimental studies demonstrate that increasing CO_2 concentrations leads to a decrease in transpiration and increase in intrinsic water use efficiency (iWUE, the ratio of photosynthesis to stomatal conductance, Leakey *et al.*, 2009), which may act to offset climate-driven ET increases or precipitation decreases to some extent (Luo *et al.*, 2008). A two-year experimental study also showed that warming can also decrease grassland transpiration by leading to earlier spring senescence (Zavaleta *et al.*, 2003b). Historical changes in iWUE can be inferred from records of stable carbon isotopes in woody plants (Peñuelas *et al.*, 2011) and even the bodies of herbivores (Barbosa *et al.*, 2010) since iWUE has been shown to be related to the change in the carbon isotope discrimination $\Delta^{13}C$ (Duquesnay *et al.*, 1998). A meta-analysis of studies at 47 sites across 5 ecosystem types (Peñuelas *et al.*, 2011) suggests that iWUE for mature trees increased by 20.5% between the 1970s and 2000s. Increased iWUE since pre-industrial times (1850 or before) has also been found at several forest sites (Gagen *et al.*, 2011; Andreu-Hayles *et al.*, 2011; Loader *et al.*, 2011; Nock *et al.*, 2011) and also in a temperate semi-natural grassland since 1857 (Koehler *et al.*, 2010), although in one boreal tree species iWUE ceased to increase after 1970 (Gagen *et al.*, 2011).

4.3.2.5. Changes in Species Range, Abundance and Extinction

Species respond to climate change through genotypic and phenotypic adaptation, by moving out of unfavorable and into favorable climates, or by going locally or globally extinct (Dawson *et al.*, 2011, Bellard *et al.*, 2012; section 4.2.2). These responses to climate change can potentially have large impacts on biodiversity and ecosystem services. Genotypic adaptation in the face of strong selection pressure from climate change is typically accompanied by large reductions in abundance (see section 4.4.1.2). Species range shifts are accompanied by changes in abundance, local extinctions and colonization that can alter ecosystem services when they affect dominant species such as trees, keystone species such as pollinators, or species that are vectors for disease. Global extinctions result in the permanent loss of unique combinations of genes.

Substantial evidence has accumulated since the AR4 report reinforcing the conclusion that terrestrial plant and animal species' ranges have moved in response to warming over the last several decades and that this movement is projected to accelerate over the coming decades under high rates of climate change. Some changes in species abundances appear to be linked to climate change in a predictable manner with species abundances increasing in areas where climate has become more favorable and vice versa. In contrast, uncertainties concerning attribution of recent and projections of future global species extinctions due to climate change have become more apparent since the AR4 report.

Observed Species Range Shifts - The number of studies looking at observed range shifts and the breadth of species examined has greatly increased since the AR4 report. The most important advances since AR4 concern improvements in understanding the relationship between range shifts and changes in climate over the last several decades. The "uphill and poleward" view of species range shifts in response to recent warming (Parmesan and Yohe, 2003; Parmesan, 2006; Fischlin *et al.*, 2007; Chen *et al.*, 2011) is an useful simplification of species response to changing climate. However, responses to warming are conditioned by changes in precipitation, land use, species interactions and many other factors. Investigations of the mechanisms underlying observed range shifts show that climate signals can often be detected, but the impacts of and interactions between changing temperature, precipitation and land use often result in range shifts that are downhill or away from the poles (Rowe *et al.*, 2010; Crimmins *et al.*, 2011; Hockey *et al.*, 2011; McCain and Colwell, 2011; Rubidge *et al.*, 2011; Pauli *et al.*, 2012;

Tingley *et al.*, 2012; Zhu *et al.*, 2012). There are large differences in the ability of species groups and species within species groups to track changes in climate through range shifts (Angert *et al.*, 2011; Mattila *et al.*, 2011; Chen *et al.*, 2011). For example, butterflies appear to be able track climate better than birds (community shifts - Devictor *et al.*, 2012; but see Chen *et al.* (2011 for range shifts) while some plants appear to be lagging far behind climate except in mountainous areas (Bertrand *et al.*, 2011; Doxford and Freckleton, 2012; Gottfried *et al.*, 2012; Zhu *et al.*, 2012). There is also growing evidence that responses at the "trailing edge" of species distributions (i.e., local extinction in areas where climate has become unfavorable) are often less pronounced than responses at the "leading edge" (i.e., colonization of areas where climate has become favorable), which may be related to differences in the rates of local extinction vs. colonization processes (Doak and Morris, 2010; Chen *et al.*, 2011**;** Brommer *et al.*, 2012; Sunday *et al.*, 2012) and difficulties in detecting local extinction (Thomas *et al.*, 2006).

Rates of recent climate change have varied greatly across the globe ranging from rapid warming to cooling (Burrows *et al.*, 2011; Dobrowski *et al.*, 2013), so taking into account this spatial variation should enhance the ability to detect climate related range shifts. A recent synthesis of range shifts indicates that terrestrial animal species have moved at rates that correspond better with changes in temperature when climate is measured in the regions where the range shifts were observed (Chen *et al.*, 2011), providing greater confidence in attributing range shifts than from range data alone. Average range shifts across taxa and regions in this study were 17 km poleward and 11 m up in altitude per decade, which are 2 to 3 times greater than previous estimates (compare with Parmesan and Yohe, 2003; Fischlin *et al.*, 2007). However, even this approach is an oversimplification since key climate drivers of species range modifications, e.g., temperature and precipitation, frequently have shifted in divergent geographical directions (Dobrowski *et al.*, 2013). Disentangling these conflicting climate signals can help explain complex responses of species ranges to changes in climate (Tingley *et al.*, 2012). Overall, studies since the AR4 report show that species range changes are complex responses to interactions among climate drivers and between climate and non-climate factors. It is the greater understanding of these interactions, combined with increased geographical scope and breadth of species studied that provides *medium confidence* that species ranges have responded to recent changes in climate.

Future Range Shifts - Projections of future species range shifts since AR4 report have been dominated by studies using ecological niche models (ENMs) that estimate future ranges based on current relationships between climate and species distribution (also called “species distribution models”, or "bioclimatic models" when models depend entirely on climate factors; Peterson *et al.*, 2011). A variety of process-based species distribution models are also being developed and more widely used (Kearney *et al.*, 2009; Dawson *et al.*, 2011; Cheaib *et al.*, 2012). Recent model comparisons suggest that in some instances bioclimatic models predict larger range shifts than process-based models (Morin and Thuiller, 2009; Kearney *et al.*, 2010; Cheaib *et al.*, 2012) although in other cases process-based models predict larger shifts (Buckley *et al.*, 2012). Projected future species shifts are broadly coherent with species responses to climate change in the paleontological record and with observed recent species shifts (see section 4.2.2 and above). There has been some progress in model validation, such as the use of hindcasting of observed recent or paleontological range shifts, but validation still needs to be reinforced using a wide array of data types (Green *et al.*, 2008; Pearman *et al.*, 2008; Nogues-Bravo *et al.*, 2010; Dawson *et al.*, 2011). A major limitation of these models is that the vast majority do not account for realistic species displacement rates (i.e., rates at which species are able to shift their ranges); as such, they only indicate changes in areas of favorable and unfavorable climate from which possible shifts in species distribution can be inferred.

A small, but growing number of new analyses and models developed since the A4 report permit the estimation the ability of a large range of species to track climate change. These projections are based on i) past and future climate velocity, which is a measure of the rate of climate displacement across a landscape and provides an indication of the speed at which an organism would need to move in order to keep pace with the changing climatic conditions (Loarie *et al.*, 2009; Burrows *et al.*, 2011; Chen *et al.*, 2011; Sandel *et al.*, 2011; Schippers *et al.*, 2011; Feeley and Rehm, 2012; Schloss *et al.*, 2012; Dobrowski *et al.*, 2013) and ii) species displacement rates across landscapes with and without habitat fragmentation for very broad range of species (e.g., Stevens *et al.*, 2010b; Nathan *et al.*, 2011; Barbet-Massin *et al.*, 2012; Kappes and Haase, 2012; Meier *et al.*, 2012; Schloss *et al.*, 2012; see additional references in Figure 4-6 legend). Figure 4-6 provides a simplified comparison of these rates as means of illustrating the projected abilities of species to track climate. This simplified analysis is coherent with more realistic projections of climate induced species displacement across landscapes, some of which include additional constraints such as habitat fragmentation or competition (Barbet-Massin *et al.*, 2012; Meier *et al.*, 2012; Schloss *et al.*, 2012). Comparison of these rates indicates whether species are projected to be able to track climate as it changes, i.e., when species displacement capacity exceeds climate velocity. When displacement rates are lower than projected climate velocities this indicates that species may be unable to keep pace with climate change.

Rates of climate change over the 20th and projected for the 21st century are shown in Figure 4-6A. Rates of climate change for global land surfaces are given for IPCC AR5 climate projections for a wide range of greenhouse gas emissions scenarios (i.e., IPCC RCP scenarios, Knutti and Sedlacek, 2012). Rates of global warming for land surfaces have averaged ca. 0.03 °C/yr since 1980. At the low end of projected future rates of warming, rates decrease over time reaching near zero by the end of the century (RCP 2.6). At the high end, projected rates increase over time and culminate above 0.06 °C/yr by the end of the century (RCP 8.5), and can exceed 0.08 °C/yr at the upper bound for this scenario. Background colors in Figure 4-6A indicate the degree to which species may be able or unable to track suitable climates based on corresponding climate velocities (Figure 4-6B) and rates of displacement for a broad range of species groups (Figure 4-6C). Blue background color indicates that nearly all species will be able to track climate change in all areas; orange indicates that some species will be unable to track climate especially in flat areas; and red indicates that many species groups will be unable to track climate except in mountainous regions.

Climate velocity depends on regional rates of climate change and the degree of altitudinal relief (Figure 4-6B, Loarie *et al.*, 2009; Dobrowski *et al.*, 2013). For example, climate velocity is low in mountainous areas, because climatic gradients are strong, and in areas where climate change is low (Figure 4-6B, leftmost axis). Climate velocity is high (Figure 4-6B, rightmost axis) in flat areas (e.g., Amazon basin) or areas where projected climate change is high (e.g., Arctic regions). In flat areas, climate velocity may exceed 8 km/yr for the highest rates of projected climate change (SRES A2 or RCP 8.5).

Rates of displacement vary greatly within and among species groups (Figure 4-6C). Some species groups, notably plants and especially trees, have very low displacement capacity. Other species groups such as butterflies, birds and large vertebrates generally have a very high capacity to disperse across landscapes. Small-ranged species across several groups (amphibians, mammals and birds) are markedly absent from areas with high climate velocities in the past, suggesting a low dispersal capacity (Sandel *et al.*, 2011). Current and future rates of climate change correspond to climate velocities that exceed rates of displacement for several species groups for most climate change scenarios. This is particularly true for mid- and late-successional trees that have maximum displacement rates that are on the order of 10s to a few 100s of m/yr. Overall, many plant species are foreseen to be able to track climates only in areas of mountainous areas, though there is uncertainty concerning the potential role of long-distance dispersal (Pearson, 2006). Primates have substantially higher dispersal capacity than trees; however, a large fraction of primates are found in regions with very high climate velocities (e.g., the Amazon basin), thereby putting them at high risk of being unable to track climates even at relatively low rates of climate change. On a global average, many rodents, as well as some carnivores and freshwater mollusks are projected to be beyond their limits to track climate at high rates of climate change (i.e., >0.06°C/yr). These projected differences in species ability to keep pace with future climate change are broadly coherent with observations of species ability or inability to track recent global warming (see above).

Humans can enhance species displacement by intentionally or unintentionally dispersing individuals or propagules (arrow on right of Figure 4-6C pointing upwards). For example, many economically important tree species may be deliberately moved on large scales as part of climate adaptation strategies in forestry in some regions (Lindner *et al.*, 2010). Human activities can also substantially reduce displacement rates. For example, habitat fragmentation typically reduces displacement rates, sometimes substantially (Eycott *et al.*, 2012; Hodgson *et al.*, 2012; Meier *et al.*, 2012; Schloss *et al.*, 2012; arrow on right pointing downwards). The degree to which habitat fragmentation slows displacement depends on many factors including the spatial pattern of fragmentation and corridors, maximum dispersal distances, population dynamics and the suitability of modified habitats as stepping-stones (Pearson and Dawson, 2003).

Species that cannot move fast enough to keep pace with the rate of climate change will lose favorable climate space and potentially experience large range contractions, whereas displacement that keeps pace with climate change may allow some species to increase their range size (Menéndez *et al.*, 2008; Pateman *et al.*, 2012). Mountains will provide an extremely important climate refuge for many species because the rate of displacement required to track climate is low (Figure 4-6B, Colwell *et al.*, 2008; Engler *et al.*, 2011; Gottfried *et al.*, 2012; Pauli *et al.*, 2012; but see Dullinger *et al.*, 2012). An important exception is for species that are already at the tops of mountains (or near other boundaries) – they are among the most threatened by climate change because they cannot move upwards (Thuiller *et al.*, 2005; ; Raxworthy *et al.*, 2008; Engler *et al.*, 2011; Sauer *et al.*, 2011). The consequences of losing favorable climate space are not yet well understood. A variety of lines of evidence reviewed below indicate that in the absence of adaptation this leads to declining abundance and eventually local extinction in areas of unfavorable climate, with potentially large effects on biodiversity and ecosystem services (see Box 4-2). Adaptive responses of species are discussed in section 4.4.1.

Significant uncertainties arising from translating rates of warming into climate velocities and from estimating displacement rates mean that the ability to track future climate can only be projected with *low confidence* across all species examined. For trees there is *medium confidence* in these projections due to the large number of studies of past, current and future displacement rates (*robust evidence* and *medium agreement*). Climate velocities are calculated using a variety of methods and spatial resolutions making direct comparisons difficult, so climate velocities in Figure 4-6B are based on semi-quantitative comparisons of several studies (see Figure 4-6 legend) and have only *low confidence* (*limited evidence* and *medium agreement*). For the global average climate velocity (Figure 4-6B, center axis), lowest estimates are about one third of the values on the axis (e.g. Loarie *et al.*, 2009; 0.42 km/yr ≈ 0.03 °C/yr for projected SRES A1B 21st century global land warming). Highest estimates are about four times the values on the axis (Burrows *et al.*, 2011; 2.7 km/yr ≈ 0.02 °C/yr global land warming from 1960-2009), but these high estimates may be artifacts of very large spatial resolutions used in this analysis (Dobrowski *et al.*, 2013). In addition, the rates used in this analysis are based on temperature alone and most analyses suggest that including more climate factors increases climate velocity (Feeley and Rehm, 2012; Dobrowski *et al.*, 2013). Species displacement rates are calculated based on a very wide range of methods including rates of displacement in the paleontological record, rates of current range shifts due to climate warming, models of dispersal and establishment, maximum observed dispersal distances and genetic analyses (e.g., Kinlan and Gaines, 2003; Stevens *et al.*, 2010b). There are often large differences in estimates of dispersal rates across methods (e.g., Kinlan and Gaines, 2003; Stevens *et al.*, 2010b) due to intrinsic uncertainties in the methods and differences in the mechanisms included. For example, estimates of tree displacement rates are frequently based on models or observations that explicitly or implicitly include both dispersal of seeds and biotic and abiotic factors controlling establishment of adult trees. Displacement rates of trees are often more strongly limited by establishment than dispersal (Higgins *et al.*, 2003; Meier *et al.*, 2012). It is reasonable to expect that limits on establishment could also be important for other species groups, but often only dispersal rates have been calculated (e.g., mammals, birds and phytophagous insects). As such, the displacement rates for these species may be optimistic. For some species groups such as trees, there are a wide range of published estimates of displacement rates leading to *high confidence* in the estimates in Figure 4-6C. Considerably less is known about displacement rates for other species groups in response to climate change (e.g., some mammal groups, mollusks), so we have only *low* to *medium confidence* in estimates of their dispersal capacity.

[INSERT FIGURE 4-6 HERE
Figure 4-6: (A) Rate of climate change, (B) corresponding climate velocities and (C) rates of displacement of several terrestrial and freshwater species groups in the absence of human intervention. The thin dotted red arrows give an example of interpretation. Rates of climate change of 0.03 °C/yr correspond to ca. 1.1 km/yr global average climate velocity. When compared to rates of displacement, this would exceed rates for most plants, many primates and some rodents. (A) Observed rates of climate change for global land areas are derived from CRUTEM4 climate data reanalysis, all other rates are calculated based on the average of the CMIP5 climate model ensembles for the historical period and for the future based on the four RCP emissions scenarios. The lower bound (17% of model projections are outside this bound) is given for the lowest emissions scenario and the upper bound for the highest emissions scenario. Data were smoothed using a 20-year sliding window, and rates are based means of between 17 and 30 models using one member per model. Global average temperatures at the end of the 21st century corresponding to each of the RCP scenarios are from Knutti and Sedlacek (2012). Colors in the background synthesize the ability of species to track climate through displacement. (B) Estimates of climate velocity were semi-quantitatively synthesized from seven studies using a diversity of analytical approaches and spatial resolutions (historical - Burrows *et al.*, 2011; Chen *et al.*, 2011; Dobrowski *et al.*, 2013; projected future - Loarie *et al.*, 2009;

Sandel *et al.*, 2011; Schippers *et al.*, 2011; Feeley and Rehm, 2012; Schloss *et al.*, 2012). The three axes represent estimated climate velocities are representative of mountainous areas (left), averaged across all global land area (center, usually geometric means), and regions that are flat or have high rates climate change (right). (C) Rates of displacement for terrestrial plants - predominantly based on dispersal and establishment - were derived from paleobotanical records, modern plant invasion rates and genetic analyses (Kinlan and Gaines, 2003). The box represents ~95% of the observations in Kinlan and Gaines (2003) and the bar represents a qualitative estimate of the median. Displacement estimates for trees are based on reconstructed rates of tree migration during the Holocene (Clark, 1998; Clark *et al.*, 2003; Kinlan and Gaines, 2003; McLachlan *et al.*, 2005; Nathan, 2006; Pearson, 2006) and modeled tree dispersal and establishment in response to future climate change (Higgins *et al.*, 2003; Iverson *et al.*, 2004; Epstein *et al.*, 2007; Goetz *et al.*, 2011; Nathan *et al.*, 2011; Meier *et al.*, 2012; Sato and Ise, 2012). The box represents ~95% of the estimates and the bar is a qualitative estimate of the median. Displacement rates for mammals were based on modeled dispersal rates of wide range of mammal species from Schloss *et al.* (2012). The box represents 1.5 x the inter-quartile range of the estimates in Schloss *et al.* (2012) and the bar is the median. Several groups of mammals have not been plotted because they include a relatively small number of species. Estimates for birds are based on observed rates of displacement (Chen *et al.*, 2011; La Sorte and Jetz, 2010) and on modeled dispersal rates in response to projected climate change (Schippers *et al.*, 2011; Barbet-Massin *et al.*, 2012), but very low confidence in these estimates makes it difficult to set bounds or indicate central tendency. Displacement rates for phytophagous insects are based on observed dispersal rates (Kinlan and Gaines, 2003; Stevens *et al.*, 2010b; Sekar, 2012). The qualitative estimate of median dispersal rate exceeds the highest rates on the axis and is on the order of 100 km/yr. These dispersal rates do not take into account limitations imposed by host plants and habitats. Displacement estimates for freshwater mollusks correspond to the range of dispersal given for passive plus active dispersal mechanisms for upstream movement in Kappes and Haase (2012).]

Observed Changes in Abundance and Local Extinctions - Observations of range shifts imply changes in abundance; i.e., colonization at the "leading edge" and local extinction at the "trailing edge" of ranges. Evidence that the attribution of these responses to recent changes in climate can be made with *high confidence* is reviewed above, in the AR4 report and by Cahill *et al.* (2013). Changes in abundance, as measured by changes in the population size of individual species or shifts in community structure, also have occurred within existing range limits in response to recent global warming (*high confidence*) (Thaxter *et al.*, 2010; Bertrand *et al.*, 2011;Naito and Cairns, 2011; Rubidge *et al.*, 2011; Devictor *et al.*, 2012; Tingley *et al.*, 2012; Cahill *et al.*, 2013; Ruiz-Labourdette *et al.*, 2013). More confident attribution to recent global warming is hindered by confounding factors such as disease, land use change and invasive species (Cahill *et al.*, 2013). A new tentative conclusion since the AR4 is that climate related local extinctions appear to be more strongly related to species interactions than to physiological tolerance limits (*low confidence*) (Cahill *et al.*, 2013). This gives weight to concerns that biological interactions, which are poorly understood and modeled, may play a critical role in mediating the impacts of future climate change on species abundance and local extinctions (Dunn *et al.*, 2009; Bellard *et al.*, 2012; Urban *et al.*, 2012; Hannah, 2012).

A few examples illustrate the types of changes in abundance and local extinctions that are being observed and the challenges in attributing these to recent global warming. Some of the clearest examples of climate-related changes in species populations come from high latitude ecosystems where non-climate drivers are of lesser importance. For example, both satellite data and a large number of long-term observations indicate that shrub abundance is generally increasing over broad areas of Arctic tundra, which is coherent with predicted shifts in community structure due to warming (Epstein *et al.*, 2007; Goetz *et al.*, 2011; Myers-Smith *et al.*, 2011). In the Antarctic, two native vascular plants, Antarctic pearlwort (*Colobanthus quitensis*) and Antarctic hair grass (*Deschampsia antarctica*) have become more prolific over recent decades, perhaps because they benefit more from warming of soils than do mosses (Hill *et al.*, 2011). Penguin populations have declined in several areas of the Antarctic, including a recent local extinction of an Emperor penguin population that has been attributed to regional changes in climate (Trathan *et al.*, 2011). The attribution to regional climate change is well supported, but the link to global warming is tenuous (Barbraud *et al.*, 2011).

Mountains also provide good examples of climate signals in abundance and local extinction because of very strong climate gradients. The AR4 report already highlighted these responses and the case for changes in abundance, in particular plants, has become stronger since then. For example, Pauli *et al.* (2012) reported an increase in species richness from plant communities of mountain tops in the European boreal and temperate zones due to increasing temperatures and a decrease in species richness on the Mediterranean mountain tops, probably due to a decrease in the water availability in Southern Europe. An increase in the population size of warm adapted species at high altitudes also appears to be attributable to increasing temperatures (Gottfried *et al.*, 2012). However, these attributions are complicated by other anthropogenic influences such as changes in grazing pressure, atmospheric nitrogen deposition, and forest management practices (Gottfried *et al.*, 2012). Altitudinal gradients in local and global extinctions of amphibians also contributed to the attribution of these extinctions to recent global warming, although this attribution remains controversial (see below).

Projected Changes in Abundance and Local Extinction - Ecological niche models do not predict population changes, but the shifts in suitable climates can be used to infer areas where species populations might decline or increase. Projected areas of local extinction from these types of models ranging from near 0% of the current range to more than 95% (Settele *et al.*, 2008; Bellard *et al.*, 2012), and projected local colonization rates are equally variable. There has been progress in coupling species distribution and species abundance models for a wide range of organisms (Keith *et al.*, 2008; Midgley *et al.*, 2010; Matthews *et al.*, 2011; Schippers *et al.*, 2011; Oliver *et al.*, 2012; Renwick *et al.*, 2012). These approaches have the substantial advantage of predicting extinction risk directly, rather than by inference from changes in climate suitability (Fordham *et al.*, 2012). The main conclusion from these studies is species response to climate change is determined by a combination of factors, including its environmental niche, demographics and life history traits, as well as interactions among these factors (Aiello-Lammens *et al.*, 2011; Conlisk *et al.*, 2012; Fordham *et al.*, 2012; Swab *et al.*, 2012).

Changes in abundances will also be accompanied by changes in genetic diversity. At an intraspecific level, future climate change projections are projected to induce severe losses of genetic diversity (Balint *et al.*, 2011). In addition, there is theoretical and observational evidence that range contractions will reduce genetic diversity (Pauls *et al.*, 2013), but that the loss of genetic diversity will depend on rates of migration and range contraction (Arenas *et al.*, 2012). Reductions in genetic diversity may then decrease the ability of species to adapt to further climate change or other global changes. Although future projections of climate change impacts do not appear to result in the loss of more phylogenetic diversity than expected by chance, projected species losses are projected to lead to phylogenetic homogenization across European plant, bird and mammal communities (Thuiller *et al.*, 2011, but see Davies *et al.*, 2011). Climate change may also compound losses of genetic diversity that already occurring due other global changes such as the introduction of alien species or habitat fragmentation (Winter *et al.*, 2009; section 4.2.4.6).

Observed Global Extinctions - Global species extinctions, many of them caused by human activities, are now close to the upper limits of observed natural rates of extinction in the fossil record (Barnosky *et al.*, 2011). Most extinctions over the last several centuries can be attributed to habitat loss, overexploitation or invasive species (Millennium Ecosystem Assessment, 2005a; Hofmann and Todgham, 2010; Cahill *et al.*, 2013). Of the more than 800 global extinctions documented by the IUCN, only 20 have been tenuously linked to recent climate change (Cahill *et al.*, 2013). Mollusks, especially freshwater mollusks, have by far the highest rate of documented extinctions of all species groups (Barnosky *et al.*, 2011). Mollusk extinctions are primarily attributed to invasive species, habitat modification and pollution — changes in climate are rarely evoked as a driver (Lydeard *et al.*, 2004; Regnier *et al.*, 2009; Chiba and Roy, 2011; but see a few cases in Kappes and Haase, 2012; Cahill *et al.*, 2013). Freshwater fish have the highest documented extinction rates of all vertebrates, and again very few have even been tenuously attributed to changing climate (Burkhead, 2012; Cahill *et al.*, 2013). In contrast, changes in climate have been identified as one of the key drivers of extinctions of amphibians (Pounds *et al.*, 2006). There have been more than 160 probable extinctions of amphibians documented over the last two decades, many of them in Central America (Pounds *et al.*, 2006; Kiesecker, 2011). The most notable cases have been the golden toad and Monteverde harlequin frog (*Atelopus varius*) of Central America, which belong to a group of amphibians with high rates of extinction ascribed to global warming with "very high confidence" (Pounds *et al.*, 2006; Fischlin *et al.*, 2007). This case has raised a number of important issues about attribution since i) the proximate causes of extinction of these and other Central American frogs appear to be an extremely virulent invasive fungal infection and land use change, with regional changes in climate as a potential contributing factor and ii) changes in regional climate may have been related to natural climate fluctuations rather than anthropogenic climate change (Sodhi *et al.*, 2008; Lips *et al.*, 2008; Collins, 2010; Anchukaitis and Evans, 2010; Vredenburg *et al.*, 2010; Kiesecker, 2011; McKenzie and Peterson, 2012; McMenamin and Hannah, 2012). While this case highlights difficulties in attribution of extinctions to recent global warming, it also points to a growing consensus that it is the interaction of climate change with other global change pressures that poses the greatest threat to species (Pereira *et al.*, 2010; Hof *et al.*, 2011; Brook *et al.*, 2008). Overall, there is *very low confidence* that observed species extinctions can be attributed to recent climate warming due to the very low fraction of species for which global extinction has been ascribed to climate change and tenuous nature of most attributions.

Projected Future Species Extinctions - Projections of future extinctions due to climate change have received considerable attention since the AR4 report. The AR4 report stated with *medium confidence* "that approximately 20-30% of the plant and animal species assessed to date are at increasing risk of extinction as global mean temperatures exceed a warming of 2-3°C above pre-industrial levels" (Fischlin *et al.*, 2007). All model-based analyses since the AR4 broadly confirm this concern, leading to *very high confidence* that climate change will contribute to increased extinction risk for terrestrial species over the coming century (Pereira *et al.*, 2010; Sinervo *et al.*, 2010; Pearson, 2011; Warren *et al.*, 2011; Hannah, 2012; Ihlow *et al.*, 2012; Bellard *et al.*, 2012; Sekercioglu *et al.*, 2012; Wearn *et al.*, 2012). More generally, there is broad agreement that climate change will result in shifts in species' ranges and abundances, and that in the context of habitat fragmentation and other global change pressures this will contribute substantially to increased extinction risk of terrestrial species over the coming century (Pereira *et al.*, 2010).

However, work since the AR4 also calls into question the ability of models to accurately quantify future extinction risk. Modeling studies have used a wide range of methods to estimate future extinction risk, generally inferring extinction risk indirectly from changes in availability of habitat and rarely taking into account demographic factors such as dispersal ability and generation time (Akcakaya *et al.*, 2006). All studies project increased extinction risk by the end of the 21st century due to climate change, but these estimates range from below 1% to above 50% of species in the groups that have been studied (Pereira *et al.*, 2010; Bellard *et al.*, 2012; Cameron, 2012). However, most models do not incorporate key processes that link climate change to population change. For example, models rarely account for genetic and phenotypic adaptive capacity, dispersal, the effects of habitat fragmentation and loss, and community interactions as well as, in plants, the effects of rising CO_2 concentrations. A general paucity of approaches to model validation, the large variation in the climate sensitivity of species groups and uncertainties about timescales involved in range reduction to extinction all lead to *very low confidence* that models currently predict extinction risk accurately (Kuussaari *et al.*, 2009; Pereira *et al.*, 2010; Dawson *et al.*, 2011; Pearson, 2011; McMahon *et al.*, 2011; Araujo and Peterson, 2012; Bellard *et al.*, 2012; Fordham *et al.*, 2012; Kramer *et al.*, 2012; Hannah, 2012; Zurell *et al.*, 2012; Halley *et al.*, 2013). In addition, evidence from the paleontological record indicating very low extinction rates over the last several hundred thousand years of substantial natural fluctuations in climate - with a few notable exceptions such as large land animal extinctions during the Holocene - has also led to concern that forecasts of very high extinction rates due entirely to climate change may be overestimated (Botkin *et al.*, 2007; Willis and Bhagwat, 2009; Pereira *et al.*, 2010; Dawson *et al.*, 2011; Hof *et al.*, 2011; Willis and MacDonald, 2011; Wake, 2012). On the other hand, processes not accounted for in most models, such changes in biotic interactions such as pollination or predator-prey networks or non-linear changes in ecosystems with widespread consequences for resident species, mean that future extinction risks may also have been substantially underestimated, at least for certain areas and species groups (Schweiger *et al.*, 2008; Bellard *et al.*, 2012; Urban *et al.*, 2008; Nakazawa and Doi, 2012; Hannah, 2012) or overestimated (Menéndez *et al.*, 2008; Pateman *et al.*, 2012). Finally, there is growing awareness that most modeling analyses have not accounted for climatic variation at fine spatial scales (microclimate) that may increase (Randin *et al.*, 2009; Gillingham *et al.*, 2012; Suggitt *et al.*, 2012; Dobrowski *et al.*, 2013; Franklin *et al.*, 2013) or decrease (Trivedi *et al.*, 2008; Engler *et al.*, 2011) the likelihood of persistence of small populations under future climate change.

4.3.3 Impacts on Major Systems

This section covers impacts of climate change on broad types of terrestrial and freshwater ecosystems of the world. We have placed a particular emphasis on those areas of high vulnerability due to high exposure to climate change or that may be pushed past thresholds or "tipping points" by climate change.

Figure 4-7 provides an overview of two perspectives on estimating ecosystem vulnerability to climate change at the global scale. Figures 4-7A and 4-7B show projected future climate change in relationship to current inter-annual variability (Diffenbaugh and Giorgi, 2012; see similar analyses by Beaumont *et al.*, 2011; Williams *et al.*, 2007b).

This analysis highlights those areas where interannual variability is low compared to projected changes in climate, i.e., where future climate is likely to be outside of temperature fluctuations already experienced by ecosystems (Beaumont *et al.*, 2011; Diffenbaugh and Giorgi, 2012). In this analysis, it is the species and ecosystems around the equator that are projected to be the most exposed to the largest climate changes. High latitude systems do not appear as exposed to climate change in this analysis because they already experience high interannual variability. A number of lines of evidence suggest that this index of climate change is an appropriate way to view species and ecosystem vulnerability. In particular, there is evidence that tropical species have evolved to have narrow thermal limits due to low inter and intra-annual climate variability, and are also already near their upper thermal limits (ectotherms - Deutsch *et al.*, 2008; Huey *et al.*, 2012; birds - Sekercioglu *et al.*, 2012; trees - Corlett, 2011). On this basis, tropical species and ecosystems are predicted to be more sensitive to climate change than species and ecosystems where intra- and inter-annual variability in climate is high (e.g., Arctic and boreal ecosystems). However, there a number of physiological, evolutionary and ecological arguments that species and ecosystem vulnerability to climate change is considerably more complex (Corlett, 2011; Laurance *et al.*, 2011; Gunderson and Leal, 2012; Walters *et al.*, 2012, Gonzalez *et al.*, 2010). Figure 4-7C compares future and contemporary climate focusing on the absolute differences between future and current climates. In this case, high northern latitude systems have the greatest exposure to rising temperature (often exceeding 6°C in the RCP 8.5 scenario, Figure 4-7C), which all else being equal would make them more vulnerable to climate change. Indeed, the greatest degree of recent climate warming has occurred at high Northern latitudes (Burrows *et al.*, 2011) and the strongest and clearest signals of recent climate warming impacts on ecosystems come from these regions. A comparison of modeled biome level vulnerability indicated that temperate and high northern latitude systems are also the most vulnerable in the future (Gonzalez *et al.*, 2010). There has been a tendency to oppose these two points of view; i.e., tropics are most vulnerable due to limited capacity of species to adapt to moderate global warming vs. high northern latitude systems are the most vulnerable because temperature increases are projected to the greatest at these latitudes. There are, however, there are good indications that both types of systems are highly vulnerable, but for different reasons (Corlett, 2011). This analysis highlights some of the reasons why there is a particularly strong focus on climate change impacts on tropical and high latitude systems in the following sub-chapters.

[INSERT FIGURE 4-7 HERE
Figure 4-7: Two climate indexes related to the vulnerability of terrestrial biomes to future climate change based on the RPC 8.5 scenario and the CMIP5 climate model ensemble (from Diffenbaugh and Giorgi, 2012). Panels A and B show the evolution of June-August temperatures in two ca. 20 year time slices around 2055 and 2090 in comparison with the hottest year during the period 1980-2005. Climate change is projected to result in many areas of the tropics and sub-tropics exceeding the temperatures during the 1980-2005 period 100% of the time by 2055. High northern latitude systems exceed this limit less frequently especially in the 2055 time slice. Panel C shows the absolute temperature differences between the 1980-2005 reference period and the 2090 time slice. High northern latitudes are exposed to much greater temperature increases than other regions and this is representative of the regional patterns of climate change for all time slices and emissions scenarios.]

An issue that emerged in the AR4 report and has grown substantially in prominence since then is that of thresholds or ‘tipping points’ (Lenton *et al.*, 2008; Scheffer *et al.*, 2009; Leadley *et al.*, 2010). Tipping points occur when positive feedback processes dominate over negative feedback loops, and the system begins to change as a result of both its internal dynamics and the external forcings, leading to a change in state that is difficult or slow to reverse (Lenton *et al.*, 2008; Scheffer *et al.*, 2009; Leadley *et al.*, 2010). In the AR5, tipping points are considered “a level of change in system properties beyond which a system reorganizes, often abruptly, and persists in its new state even if the drivers of the change are abated” (Glossary). Many examples of such thresholds have now been identified (Scheffer, 2009). Most are at the local scale, but the potential existence of ecological thresholds at a sufficient scale to have regional or global consequences is high. Posited examples include a drought and temperature threshold in the Amazon beyond which forest dieback and fires could contribute to large C fluxes to the atmosphere, or thawing of Arctic permafrost leading to emissions of CH_4 and CO_2 in sufficient quantities to further warm the Earth and amplify the permafrost warming (Lenton *et al.*, 2008; Leadley *et al.*, 2010). Ecosystem water balance thresholds that are surpassed through changes in temperature and precipitation, both gradual and through extreme events, may be a widespread phenomenon across a range of biomes (Knapp *et al.*, 2008a). Large-scale tipping points have not occurred in the recent past, but there is good evidence for tipping points in the distant past (section 4.2.2) and the sub-sections below highlight reasons for concern that they could occur in the near future. A thorough analysis of all the highlighted tipping points is not possible in this section, so we have highlighted some of the most important and well-studied tipping points. Others are discussed in Lenton *et al.* (2008) and Leadley *et al.* (2010).

4.3.3.1. Forests and Woodlands

Forests and woodlands, are the principal providers of timber and pulp, biofuel and an important and steady source of good-quality water worldwide. They also supply other services, including food and, cultural services such as recreation. Forests are the habitat of a large fraction of the earth's terrestrial biodiversity, especially in tropical regions (Gibson *et al.*, 2011). Climate change and forests interact strongly. Climate and atmospheric CO_2 concentrations are major drivers of forest productivity and forest dynamics. At the same time forests play an important role in controlling climate through the large amounts of carbon they can store or release, and through direct effects on the climate such as the absorption or reflection of solar radiation (albedo), cooling through evapotranspiration and the production of cloud-forming aerosols (Arneth *et al.*, 2010;Pan *et al.*, 2011; Pielke *et al.*, 2011).

Combinations of ground based observations, atmospheric carbon budgets and satellite measurements indicate that forests are currently a net sink for carbon at the global scale. It is estimated that intact and regrowing forests currently contain 861±66 PgC and stored 4.0 ± 0.7 Pg C year^{-1} globally between 2000 and 2007 (Pan *et al.*, 2011; WG1 Chapter 6; Canadell *et al.*, 2007; Le Quere *et al.*, 2009). The carbon stored in intact and regrowing forests was counterbalanced by a release due to land-use change of 2.8±0.4 Pg C year^{-1} over this same period due to tropical deforestation, resulting in a net C balance for global forests of 1.2±0.8 Pg C year^{-1}.

The phrase 'biophysical effects' is shorthand for the effect forests have on the climate other than through being sources and sinks of greenhouse gases. These effects are now well documented, significant and are increasingly included in models of global and regional climate change. Observations and models indicate that boreal and tropical forests have the largest influence on climate, but for different reasons: boreal forests have low albedo (i.e., reflect less solar radiation); and tropical forests pump more water and aerosols into the atmosphere than non-forest systems in similar climates (Davin and de Noblet-Ducoudre, 2010; Delire *et al.*, 2011; Pielke *et al.*, 2011). Overall, this means that the biophysical effect of boreal forests is to warm the atmosphere and tropical forests to cool the atmosphere, compared to non-forest systems (Davin and de Noblet-Ducoudre, 2010). It has also been shown that forests influence regional precipitation through biophysical effects: deforestation in the tropics can alter regional precipitation (Butt *et al.*, 2011) and there is growing evidence of similar effects in temperate forests (Pielke *et al.*, 2011).

The future of the interaction between climate and forests is unclear. The carbon stored by intact and regrowing forests appears have stabilized compared to the 1990's, after having increased in the 1970's and 1980's (Canadell *et al.*, 2007; Pan *et al.*, 2011). The drivers behind the forest carbon sink vary greatly across regions. They include forest regrowth and simulation of C sequestration by climate change, rising atmospheric CO_2 concentrations and N deposition (Pan *et al.*, 2011). Most models suggest that rising temperatures, drought and fires will lead to forests becoming a weaker sink or a net carbon source before the end of the century (Sitch *et al.*, 2008; Bowman *et al.*, 2009). Fires play a dominant role in driving forest dynamics in many parts of the world and the susceptibility to fire is projected to increase little for the lowest emissions scenario (RCP 2.6), but substantially for the high emissions scenario (RCP 8.5, Figure 4-8). Climate change-mediated disease and insect outbreaks could precipitate this transition (Kurz *et al.*, 2008). The greatest risks for large feedbacks from forests to climate arise from widespread tree mortality and fire in tropical forests and low latitude areas of boreal forests, as well as northward expansion of boreal forests into arctic tundra (Lenton *et al.*, 2008; Kriegler *et al.*, 2009; Good *et al.*, 2011).

[INSERT FIGURE 4-8 HERE
Figure 4-8: Forest Fire Danger Index (FFDI) and its changes simulated with the HadGEM2-ES Earth System Model (Jones *et al.*, 2011). Left column: 30-year mean FFDI (MacArthur, 1973; Noble *et al.*, 1980) for 1980-2010 (top) and 2070-2100 under RCP2.6 (middle) and RCP8.5 (bottom). Right column: differences in 30-year mean FFDI relative to 1980-2010 for 2070-2100 under RCP2.6 (middle) and RCP8.5 (bottom). Maps show 30-year means of

FFDI values calculated using daily model data, following the methodology of (Golding and Betts, 2008). FFDI is not shown where the simulated vegetation cover is less than 10% for the respective time period (colored grey).]

Recent evidence suggests that the stimulatory effects of global warming and rising CO_2 concentrations on tree growth may have already peaked in many regions (Charru *et al.*, 2010; Silva *et al.*, 2010; Silva and Anand, 2013) and that warming and changes in precipitation are increasing tree mortality in a wide range of forest systems, acting via heat stress, drought stress, pest outbreaks and a wide range of other indirect impact mechanisms (Allen *et al.*, 2010a; Box 4-2). Detection of a coherent global signal is hindered by the lack of long-term observations in many regions, and attribution to climate change is difficult due to the multiplicity of mechanisms mediating mortality (Allen *et al.*, 2010a).

Deforestation has slowed over the last decade (Meyfroidt and Lambin, 2011). This includes substantial reductions in tropical deforestation in some regions, such as the Brazilian Amazon, where deforestation rates declined rapidly after peaking in 2005 (Secretariat of the Convention on Biological Diversity, 2010). It is unclear if the global trend to reduced forest loss will continue - there are substantial pressures to deforest for the production of food and biofuels (Wise *et al.*, 2009; Meyfroidt and Lambin, 2011). However, there are a number of signs that tropical deforestation could slow substantially over the next few decades, although this is thought to require continued and substantial technological, institutional and policy innovations (Wise *et al.*, 2009; Meyfroidt and Lambin, 2011; Westley *et al.*, 2011).

_____ START BOX 4-2 HERE _____

Box 4-2. Tree Mortality and Climate Change

Extensive tree mortality and widespread forest die-off linked to drought and temperature stress have been documented recently on all vegetated continents (Allen *et al.*, 2010a; Figure 4-9). Plot level datasets with appropriate spatial and temporal spans to detect long-term tree mortality trends (>20 years) are currently lacking for many regions (Anderegg *et al.*, 2013a), leading to *low confidence* in the ability to detect a global trend. Nevertheless, long-term increasing tree mortality rates associated with temperature increases and drought have been documented in boreal and temperate forests in western North America (van Mantgem *et al.*, 2009; Peng *et al.*, 2011). Increased levels of tree mortality following drought episodes have also been detected across widespread plot networks in multiple tropical forests (Kraft *et al.*, 2010; Phillips *et al.*, 2010) and Europe (Carnicer *et al.*, 2011). Episodes of widespread die-off (high mortality rates of dominant tree species at a landscape scale) have been observed in multiple vegetation types, particularly in western North America, Australia, and southern Europe (Raffa *et al.*, 2008; Carnicer *et al.*, 2011; Anderegg *et al.*, 2013b). Some widespread die-off events have occurred concomitant with infestation outbreaks (Raffa *et al.*, 2008), where pest populations are also directly influenced by climate, such as population release by warmer winter temperatures (Bentz *et al.*, 2010). While strong attribution of extensive tree mortality to recent warming has been made in a few studies, the paucity of long-term studies of the mechanisms driving mortality means that there is *low confidence* that this attribution can be made at the global scale.

Widespread die-off has influenced the species composition, structure and age demographics, and successional trajectories in these forests, and in some cases led to decreased plant species diversity and increased risk of invasion (Kane *et al.*, 2011; Anderegg *et al.*, 2012). Widespread mortality also has multiple effects on biosphere-atmosphere interactions and could play an important role in future carbon-cycle feedbacks through complex effects on forest biophysical properties and biogeochemical cycles (Breshears *et al.*, 2005; Kurz *et al.*, 2008; Anderson *et al.*, 2011).

Projections of tree mortality due to climate stress and potential thresholds of widespread forest loss are currently highly uncertain (McDowell *et al.*, 2011). Most current global scale vegetation models have little-to-no mechanistic representation of tree mortality (Fisher *et al.*, 2010; McDowell *et al.*, 2011). Nonetheless, a global analysis of tree hydraulic safety margins found that more than 70% of surveyed tree species operate close to their limits of water stress tolerance (Choat *et al.*, 2012), indicating that vulnerability to drought and temperature stress will not be limited to arid and semi-arid forests. Furthermore, timescales of tree and plant community recovery following drought are largely unknown, but preliminary evidence from several systems indicates recovery times may be shorter than recent drought return intervals, leading to “compounding” effects of multiple droughts (Mueller *et al.*, 2005; Anderegg *et al.*, 2013b; Saatchi *et al.*, 2013). Projected increases in temperature are also expected to facilitate expansion of insect outbreaks poleward and up in altitude, which may also cause or contribute to widespread tree mortality (Bentz *et al.*, 2010).

[INSERT FIGURE 4-9 HERE
Figure 4-9: Locations of observed drought- and heat-induced tree mortality around the Earth since 1970, documented by peer-reviewed studies. Global forest cover (dark green) and other wooded regions (light green) (FAO, 2005). Studies compiled through 2009 (red dots) are summarized and listed in Allen et al. (2010). Localities and measurement networks not included in Allen *et al.* (2010a), which are largely post-2009 studies, have been added to this map (white dots are specific locations and regional measurement networks are indicated by ovals). New locality references by region: Africa – Mehl *et al.* (2010); Gonzalez *et al.* (2012); van der Linde *et al.* (2011); Asia – Dulamsuren *et al.* (2009); Kharuk *et al.* (2013); Liu *et al.* (in revision); Zhou *et al.* (2013); Australasia – Brouwers *et al.* (2012, 2013); Fensham *et al.* (2012); Matusick *et al.*, 2012, 2013); Europe – Innes (1992); Peterken and Mountford (1996); Linares *et al.* (2009); Galiano *et al.* (2010); Vennetier and Ripert (2010); Aakala *et al.* (2011); Carnicer *et al.* (2011); Sarris *et al.* (2011); Marini *et al.* (2012); Vilà-Cabrera *et al.* (2012);Cailleret *et al.* (2013); North America – Fahey (1998); Barbour *et al.* (2007); Klos *et al.* (2009); Ganey and Vojta (2011); Peng *et al.* (2011); DeRose and Long (2012); Fellows and Goulden (2012); Kaiser *et al.* (2012); Kukowski *et al.* (2012); Millar *et al.*, 2012); Williams *et al.* (2012); Worrall *et al.* (2013); Garrity *et al.* (in review);South America – Enquist and Enquist (2011); Lewis *et al.* (2011); Saatchi *et al.* (2013).]

_____ END BOX 4-2 HERE _____

4.3.3.1.1. Impacts of climate change on boreal forests

Most projections suggest a poleward expansion of forests into tundra regions, accompanied by a general shift in composition towards more temperate plant functional types (e.g., evergreen needleleaf being replaced by deciduous broadleaf; or in colder regions, deciduous needleleaf replaced by evergreen needleleaf; Lloyd *et al.*, 2011; Pearson *et al.*, 2013). At the same time, projections of climate-driven changes in boreal forests over the next few centuries remain divergent on some issues, partly as a result of different processes of change being considered in different models. In particular, the inclusion or exclusion of fire and insects makes a big difference, possibly making the boreal forest more susceptible to a rapid, non-linear or abrupt decline in some regions of the circum-Northern Hemisphere (Bernhardt *et al.*, 2011; Mann *et al.*, 2012; Scheffer *et al.*, 2012). Recent change (Box 4-2) and dynamic vegetation modeling (e.g., Sitch *et al.*, 2008) provide *high confidence* that regions of the boreal forest could witness widespread forest dieback. These shifts put at risk the boreal carbon sink, estimated at 0.5 Pg year^{-1} in 2000-2007 (Pan *et al.*, 2011; Mann *et al.*, 2012).

Whereas boreal forest productivity is widely expected, with *medium confidence*, to increase as a result of warming (Hari and Kulmata, 2008; Bronson *et al.*, 2009; Zhao and Running, 2010; Van Herk *et al.*, 2011), and early analyses of satellite observations confirmed this trend in the 1980s, more recent and longer-term assessments indicate with *high confidence* that many areas of boreal forest have instead experienced productivity declines (Goetz *et al.*, 2007; Parent and Verbyla, 2010; Beck *et al.*, 2011b; de Jong *et al.*, 2011). The reasons for these “browning” trends have been debated but they are not directly related to fire disturbance (because fires produce random rather than systematic trends in time series). The best evidence to date indicates that warming-induced drought, specifically the greater drying power of air (vapor pressure deficit), induces photosynthetic down-regulation of boreal tree species, particularly conifer species, most of which are not adapted to the warmer conditions (Welp *et al.*, 2007; Bonan, 2008; Van Herk *et al.*, 2011). Satellite evidence for warming-induced productivity declines has been corroborated by tree ring studies (Barber *et al.*, 2000; Hogg *et al.*, 2008; Beck *et al.*, 2011b; Porter and Pisaric, 2011; Griesbauer and Green, 2012) and long-term tree demography plots in more continental and densely forested areas (Peng *et al.*, 2011; Ma *et al.*, 2012). Conversely, productivity has increased at the boreal-tundra ecotone where more mesic conditions support an expected warming-induced growth response (Rupp *et al.*, 2001; McGuire *et al.*, 2007; Goldblum and Rigg, 2010; Beck *et al.*, 2011b).

There is *high confidence* that warming and drying, coupled with productivity declines, insect disturbance and associated tree mortality, also favor greater fire disturbance. The boreal biome fire regime has intensified in recent decades, exemplified by increases in the extent of area burned but also a longer fire season and more episodic fires that burn with greater energy output or intensity (Girardin and Mudelsee, 2008; Macias Fauria and Johnson, 2008; Kasischke *et al.*, 2010; Turetsky *et al.*, 2011; Mann *et al.*, 2012). The latter is particularly important because more severe burning consumes soil organic matter to greater depth often to mineral soil, providing conditions that favor recruitment of deciduous species that, in the North American boreal forest, replace what was previously evergreen conifer forest (Johnstone *et al.*, 2010; Bernhardt *et al.*, 2011). Fire mediated composition changes in post-fire succession influence a host of ecosystem feedbacks to climate, including changes net ecosystem carbon balance (Bond-Lamberty *et al.*, 2007; Goetz *et al.*, 2007; Welp *et al.*, 2007; Euskirchen *et al.*, 2009) as well as albedo and energy balance (Randerson *et al.*, 2006; Jin *et al.*, 2012; O'Halloran *et al.*, 2012). The most comprehensive study to date (Randerson *et al.*, 2006) focused on a set of flux tower measurements across a composition gradient, but this study was necessarily limited to a few sites in central Alaska. The extent to which the net effect of these feedbacks will exacerbate or mitigate additional warming is not well known over the larger geographic domain of the boreal biome, except via modeling studies that are relatively poorly constrained due to sparse *in situ* observations.

There is *high confidence* that the vulnerability of the boreal biome to this cascading series of interacting processes (Wolken *et al.*, 2011), and their ultimate influence on climate feedbacks, differs between North America and northern Eurasia. The latter is dominated by deciduous conifer (larch) forest, extending from western Russia across central to eastern Siberia – a region more than twice the size of the North American boreal biome, most of it underlain by permafrost conditions of the Siberian environment. In terms of post-fire succession analogous to the North American boreal biome, larch function more like deciduous species than evergreen conifers, with greater density and biomass gain in more severely burned areas, given adequate seed survival through fire events or post-fire seed dispersal (Zyryanova, 2007; Osawa *et al.*, 2010; Alexander *et al.*, 2012). Although the fire regime has intensified in the last 100 years in Siberia, as well as in North America (Soja *et al.*, 2007; Mann *et al.*, 2012; Ali *et al.*, 2012; Marlon *et al.*, 2013), the likelihood of regime shifts in larch forests is currently unknown, partly because larch are self-replacing (albeit at different densities) and partly because it is largely dependent on the fate of permafrost across the region.

The vulnerability of permafrost to thawing and degradation with climate warming is critical not only for determining the rate of a boreal-tundra biome shift, and its associated net feedback to climate, but also for predicting the degree to which the mobilization of very large carbon stores frozen for centuries will exacerbate additional warming (Schuur *et al.*, 2008; 2009; Tarnocai *et al.*, 2009; Romanovsky *et al.*, 2010; Schaefer *et al.*, 2011; see also Section 4.3.3.4). The extent and rate of permafrost degradation varies with temperature gradients from warmer discontinuous permafrost areas to colder, more continuous areas, but also with the properties of the soil composition and biology (e.g., Mackelprang *et al.*, 2011). The degree of thermokarsting associated with different substrates, and associated topographic relief, is tremendously variable because boreal vegetation in latter successional stages (evergreen conifers in North America) insulate permafrost from air temperature increases; soils with differing silt and gravel content tend to have different ice content that, when melted, produces different degradation and deformation rates; and other factors such as fire disturbance interactions with both vegetation cover and soil organic depth as insulating layers (Jorgenson *et al.*, 2010; Grosse *et al.*, 2011). This variability, and vulnerability, is poorly represented in earth system models (McGuire *et al.*, 2012) and is thus the emphasis of research initiatives currently underway. Carbon management strategies to keep permafrost intact, for example by removing forest cover to expose the land surface to winter temperatures (Zimov *et al.*, 2009) are impractical not only because of the vast spatial domain underlain by permafrost, but also because of the broad societal and ecological impacts that would result.

4.3.3.1.2. Impacts of climate change on temperate forests

The largest areas of temperate forest are found in eastern North America, Europe and eastern Asia. The overall trend for forests in these regions has until recently been an increase in growth rates of trees and in total carbon stocks. This has been attributed to a combination of increasing growing season length, rising atmospheric CO_2 concentrations, nitrogen deposition and forest management – specifically regrowth following formerly more intensive harvesting regimes (Ciais *et al.*, 2008). The relative contribution of these factors has been the subject of substantial and unresolved debate (Boisvenue and Running, 2006). Most temperate forests are managed such that any change is and will be to a large extent anthropogenic. With the exception of Europe (Ciais *et al.*, 2008), the relative contribution of anthropogenic and environmental factors to forest growth and carbon uptake rates remains to be quantified.

The world's temperate forests act as an important carbon sink (*high confidence* due to *robust evidence; high agreement)*, absorbing 0.7±0.08 Pg C year^{-1} from 1990 to 1999 and 0.8±0.09 from 2000 to 2007 (Pan *et al.*, 2011).This represents 34% of global carbon accumulation in intact forests and 65% of the global net forest carbon sink (total sink minus total emissions from land use).

Recent indications are that temperate forests and trees are beginning to show signs of climate stress, including: a reversal of tree growth enhancement in some regions (N America - Silva *et al.*, 2010; Silva and Anand, 2013; Europe - Charru *et al.*, 2010; Bontemps *et al.*, 2011; Kint *et al.*, 2012); increasing tree mortality (Allen *et al.*, 2010a, Box 4-2); and changes in fire regimes, insect outbreaks and pathogen attacks (Adams *et al.*, 2012; Edburg *et al.*, 2012). In north-eastern France, widespread recent declines in growth rates of European beech (*Fagus sylvatica L.*) have been attributed to decreasing water availability (Charru *et al.*, 2010). These trends threaten the substantial role of temperate forests as net carbon sinks, but it is still unclear to what extent the observations are representative for temperate forests as a whole. Several studies find that tree growth rates in temperate forests passed their peak in the late 20th century and that the decline in tree growth rates can be attributed to climatic factors, especially drought or heatwaves (Charru *et al.*, 2010; Silva *et al.*, 2010). Extreme climate events have had a major impact on temperate forests over the last decade (Witte *et al.*, 2011; Kasson and Livingston, 2012; Ciais *et al.*, 2005). Extensive forest fires occurred in Russia during the exceptionally hot and dry summer of 2010 (Witte *et al.*, 2011). The complex interactions between climate and forest management in determining susceptibility to extreme events make it difficult to unequivocally attribute these events to recent climate warming (Allen *et al.*, 2010a). There is *low confidence (limited evidence; medium agreement)* that climate change is threatening the temperate forest carbon sink directly or indirectly.

At the biome level, there remains considerable uncertainty in the sign and the magnitude of the carbon cycle response of temperate forests to climate change. A comparison of DGVM models showed that for identical end of 21st century climate projections, temperate forests are variously projected to substantially increase in total (biomass plus soil) carbon storage, especially as a result of potential gains in tree cover in eastern North America and Europe; or decrease due to reductions in total carbon storage per hectare and loss of tree cover (Sitch *et al.*, 2008). Projections for eastern Asia are less variable: temperate forests remain carbon sinks over the coming century, with carbon storage generally peaking by mid-century and then declining (He *et al.*, 2007; Sitch *et al.*, 2008; Ni, 2011; Peng *et al.*, 2009). However, regional vegetation models for China predict a substantial northward shift of temperate forest (Weng and Zhou, 2006; Ni, 2011). There is little indication from either models or observations that the responses of temperate forests to climate change are characterized by tipping points. The feedback mechanisms operating in boreal and tropical forests which lead to tipping point behavior appear to be less dominant in temperate forests (Bonan, 2008). There is *low confidence (medium evidence; low agreement)* on long-term, climate-driven changes in temperate forest biomass and geographical range shifts.

At the species level, models predict that the potential climatic space for most tree species will shift poleward and up in altitude in response to climate change (Dale *et al.*, 2010; Ogawa-Onishi *et al.*, 2010; Hickler *et al.*, 2012). Associated long-term projected range shifts generally vary from several km to several tens of km per decade, most probably cannot achieve such high rates by natural migration (*e.g.* Chmura *et al.*, 2011, see also 4.3.2.5). Therefore, assisted migration has been suggested as an adaptation measure (see 4.4.2.4). Such shifts would alter biodiversity and ecosystem services from temperate forests (e.g. Dale *et al.*, 2010). Multi-model comparisons for temperate forests, however, illustrate that there are differences in species response and that models differ greatly in the severity of projected climate change impacts on species ranges (Kearney *et al.*, 2010; Kramer *et al.*, 2010; Morin and Thuiller, 2009; Cheaib *et al.*, 2012). Tree growth models project increased tree growth at the poleward and high altitudinal range limits over most of the next century in China (Ni, 2011). New approaches to modelling tree responses, based on the sensitivity of key life-history stages, suggest that climate change impacts on reproduction could be a major limitation on temperate tree distributions (Morin *et al.*, 2007). Comparisons with paleoecological data have helped improve confidence in the ability of models to project future changes in species ranges (Pearman *et* *al.*, 2008, Allen *et al.*, 2010b, Garreta *et al.*, 2010). Model projections are qualitatively coherent with observations that temperate forest species are already moving up in altitude, probably due to climate warming at the end of the 20th century (Lenoir *et al.*, 2008). There is *medium confidence (medium evidence; medium agreement)* that temperate tree and animal species are migrating poleward and upward altitudinally.

4.3.3.1.3. Impacts of climate change on tropical wet and dry forests

The responses of tropical forests to variability and change in climate and atmospheric CO_2 concentration are superimposed upon the direct influences of human activities. Humans modify the composition and structure of tropical forests through the harvest of individual plants or animals and through management interventions to favor some species or structural features over others. Humans also convert forests to cropland or grazing land and influence forest exposure to ignition sources. Forest conversion is the best understood change that is underway in tropical forests. Climate change effects on tropical forests interact with the direct influences of humans and are understood largely through field studies of the responses of forests to extreme weather events and through models that are able to simulate a growing number of ecological and atmospheric processes.

A key uncertainty in our understanding of future impacts of climate change on tropical forests is the strength of direct CO_2 effects on photosynthesis and transpiration (see section 4.3.2.4). These responses will play an important role in determining tropical forest trends as temperatures and atmospheric CO_2 concentrations rise. There is a physiological basis for arguing that photosynthesis will increase sufficiently to offset the inhibitory effects of higher temperatures on forest productivity (Lloyd and Farquhar, 2008) although heightened photosynthesis does not necessarily translate into an increase in overall forest biomass, (Körner and Basler, 2010). DGVMs and the current generation of Earth System Models, including those used within CMIP5 (e.g., Jones *et al.*, 2011) generally use formulations for CO_2 effects on photosynthesis and transpiration based on laboratory-scale work (Jarvis, 1976; Farquhar *et al.*, 1980; Ball *et al.*, 1987;Stewart, 1988; Collatz *et al.*, 1992; Leuning, 1995; Haxeltine and Prentice, 1996; Cox *et al.*, 1998) that pre-dates larger ecosystem-scale studies, although some models have been optimized on the basis of more recent data (Jones *et al.*, 2011).

A second important source of uncertainty is the rate of future CO_2 and temperature rise (Betts *et al.*, 2012). Modelled simulations of future climate in tropical forest regions indicate with *high confidence (robust evidence, high agreement*) that temperature will increase. Future precipitation change, in contrast, is highly uncertain and varies considerably between climate models (WG1 Annex A), although there is *medium confidence* (*medium evidence, medium agreement*) that some tropical regions, such as the eastern Amazon Basin, will experience lower precipitation (Malhi *et al.*, 2009b). The range of possible shifts in the moist tropical forest envelope is large, sensitive to the responsiveness of water use efficiency (WUE) to rising concentrations of atmospheric CO_2, and varies depending on the climate and vegetation model that is used (Scholze *et al.*, 2006; Zelazowski *et al.*, 2011) (Sitch *et al.*, 2008) Recent model medley studies (Cox *et al.*, 2013; Huntingford *et al.*, 2013) indicate that the future geographical range of moist tropical forests as determined by its shifting climatological envelope is *less likely* to undergo major retractions or expansions by 2100 through climate change alone as previously predicted (Cox *et al.*, 2000).

Changes in the species composition and biomass of moist tropical forests observed in networks of long-term forest plots in moist tropical forests are generally consistent with increasing WUE associated with the rising concentration of CO_2. Lianas and fast-growing tree species are increasing, as is forest biomass (Phillips *et al.*, 2002; Phillips *et al.*, 2005; Lewis *et al.*, 2009a; Lewis *et al.*, 2009b; Lewis *et al.*, 2011). Faster tree growth could also result from changes in solar radiation and the ratio of diffuse to direct radiation (Mercado *et al.*, 2009; Lewis *et al.*, 2009a; Brando *et al.*, 2010). There is *low confidence* (*limited evidence, medium agreement*) that the composition and biomass of Amazon and African forests are changing through the rise in atmospheric CO_2. The potential suppression of photosynthesis and tree growth in tropical forests through rising air temperatures is supported by physiological and eddy covariance studies (Doughty and Goulden, 2008; Lloyd and Farquhar, 2008; Wood *et al.*, 2012), but is not yet observed as changes in forest biomass (except Clark *et al.*, 2003).

Since AR4, there is new experimental and observational evidence of ecological thresholds of drought and fire in moist tropical forests that points to an important indirect role of climate change in driving large-scale changes in moist tropical forests (see Box 4-3). Forest tree mortality increased abruptly above a critical level of soil moisture depletion in two rainfall exclusion experiments (Nepstad *et al.*, 2007; Fisher *et al.*, 2008) and above a critical level of weather-related fire intensity in a prescribed burn experiment (Brando *et al.*, 2012). These experimental results were corroborated by observations of increased tree mortality during the extremely severe 2005 drought in the Amazon (Phillips *et al.*, 2009) and extensive forest fire (Alencar *et al.*, 2006; Aragão *et al.*, 2008; Alencar *et al.*, 2011; Box 4-3). There is *medium confidence* (*medium evidence, high agreement*) that moist tropical forests have many tree species that are vulnerable to drought- and fire-induced mortality during extreme dry periods. There is *low confidence* (*limited evidence, low agreement*) that the severe droughts that have affected the Amazon region are associated with climate change (Shiogama *et al.*, 2011).

There is also a growing body of evidence that severe weather events interact with land use to influence moist tropical forest fire regimes. Many moist tropical forests are not susceptible to fire during typical rainfall years because of high moisture content of fine fuels Cochrane, 2003. Selective logging, drought, and fire itself can reduce this fire resistance by killing trees, thinning the canopy and allowing greater heating of the forest interior; Uhl and Kauffman, 1990; Ray *et al.*, 2005; Curran *et al.*, 2004; Box 4-3). Land use often increases the ignition sources in tropical landscapes (Silvestrini *et al.*, 2011). These relationships are not yet represented fully in coupled climate-vegetation models. There is *high confidence* (*robust evidence, high agreement*) that forest fire frequency and severity is increasing through the interaction between severe droughts and land use.

There are an estimated one million square kilometres of dry tropical forests in the world (Miles *et al.*, 2006), defined as forests occurring in tropical regions characterized by pronounced seasonality in rainfall distribution (Mooney *et al.*, 1995). More than half of the remaining tropical dry forests (54%) are located in South America. Approximately one third of the remaining tropical forests in the Americas are predicted to experience “severe climate change” by 2055, defined as an increase in air temperate of at least 2.5 deg. C and/or a decrease in precipitation of at least 50 mm a^{-1}. Less than one fifth of forests in other tropical dry forest formations are faced with this level of climate risk (Miles *et al.*, 2006). Climate change, deforestation, fragmentation, fire, or human pressure place virtually all (97%) of the remaining tropical dry forests at risk (Miles *et al.*, 2006).

_____ START BOX 4-3 HERE _____

Box 4-3. A Possible Amazon Basin Tipping Point

Since AR4, our understanding of the potential of a large-scale, climate-induced, self-reinforcing transition of Amazon forests to a dry stable state (known as the Amazon “forest dieback”) has improved. Modeling studies indicate that the likelihood of a purely climate-driven dieback in 2100 is lower than previously thought (Malhi *et al.*, 2009b; Good *et al.*, 2013; Cox *et al.*, 2013; Huntingford *et al.*, 2013) and there is now *medium confidence* (*robust evidence, medium agreement*) that climate change alone will not lead to widespread forest loss during this century. Meteorological fire danger is projected to increase (Golding and Betts, 2008; Betts *et al.*, submitted; Figure 4-8). Field studies and regional observations, have provided new evidence of critical ecological thresholds and positive feedbacks between climate change and land-use activities that could drive a fire-mediated, self-reinforcing dieback in this century. There is now *medium confidence* (*medium evidence, medium agreement*) that severe drought episodes, land use, and fire interact synergistically to drive the transition of mature Amazon forests to low-biomass, low-statured pyrophilic woody vegetation.

Most primary forests of the Amazon Basin have damp fine fuel layers and low susceptibility to fire, even during annual dry seasons (Uhl and Kauffman, 1990; Ray *et al.*, 2005). Forest susceptibility to fire increases through canopy thinning and greater sunlight penetration caused by tree mortality associated with selective logging (Uhl and Kauffman, 1990; Ray *et al.*, 2005; Barlow and Peres, 2008), previous forest fire (Balch *et al.*, 2008; Brando *et al.*, 2012), severe drought (Alencar *et al.*, 2006), or drought-induced tree mortality (Nepstad *et al.*, 2007; da Costa *et al.*, 2010). The impact of fire on tree mortality is also weather-dependent. Under very dry, hot conditions, fire-related tree mortality can increase sharply (Brando *et al.*, 2012). Under some circumstances, tree damage is sufficient to allow light-demanding, flammable grasses to establish in the forest understory, increasing forest susceptibility to further burning (Veldman and Putz, 2011). There is *high confidence* (*robust evidence, high agreement*) that logging, severe drought, and previous fire increase Amazon forest susceptibility to burning.

Landscape level processes further increase the likelihood of forest fire. Ignition sources are more common in agricultural and grazing lands than in forested landscapes (Silvestrini *et al.*, 2011) (*high confidence*: *robust evidence, high agreement*), and forest conversion to grazing and crop lands can inhibit regional rainfall through changes in albedo and evapotranspiration (Costa *et al.*, 2007; Butt *et al.*, 2011; Knox *et al.*, 2011) (*low confidence*: *medium evidence*, *low agreement*) or through smoke, that can inhibit rainfall under some circumstances (Andreae *et al.*, 2004) (*low confidence*: *medium evidence, low agreement*). Apart from these landscape processes, climate change could increase the incidence of severe drought episodes (Shiogama *et al.*, 2011).

In sum, fire-mediated changes in Amazon forests are self-reinforcing through increases in tree mortality, forest susceptibility to fire, ignition sources, and regional rainfall inhibition (Figure 4-10). If current patterns of deforestation, logging, severe drought, and forest fire continue into the future, 55% of the region's forests will be cleared or degraded by 2030, even without invoking positive feedbacks with regional climate, releasing 20±10 Pg of carbon to the atmosphere (Nepstad *et al.*, 2008) (*low confidence*: *low evidence, medium agreement*). The likelihood of a tipping point being reached may decline if extreme droughts (such as 1998, 2005, and 2010) (Marengo *et al.*, 2011) become less frequent, if land management fires are suppressed, if forest fires are extinguished (Soares-Filho *et al.*, 2012), if deforestation declines, or if cleared lands are reforested (Nepstad *et al.*, 2008). The 76% decline in deforestation in the Brazilian Amazon with 80% of the region's forest still standing (INPE, 2012) demonstrates that large-scale mitigation of a fire-mediated tipping point could be feasible.

[INSERT FIGURE 4-10 HERE
Figure 4-10: The forests of the Amazon Basin are being altered through severe droughts, land use (deforestation, logging), and increased frequencies of forest fire. Some of these processes are self-reinforcing through positive feedbacks, and create the potential for a large-scale tipping point. For example, forest fire increases the likelihood of subsequent burning, especially if burning is followed by forest invasion by grasses or flammable herbs. Deforestation inhibits rainfall in the region and provides ignition sources to flammable forests, contributing to this dieback.]

_____ END BOX 4-3 HERE _____

4.3.3.2. Rangelands and Drylands, including Mediterranean-type Systems

The following sections treat a wide range of terrestrial ecosystems covering a large part of the terrestrial surface, whose unifying features are that they are not classified as forests and they typically exhibit strong water stress for several months each year. Grasses, grass-like plants and herbs are usually a major part of their vegetation cover. The principle land use often involves either wild or domestic herbivores.

4.3.3.2.1. Savannas

Savannas are defined as mixtures of coexisting trees and grasses. The geographical distribution of tropical savannas is determined by temperature, the seasonal availability of water, fire and soil conditions (Ellery *et al.*, 1991; Walker and Langridge, 1997; Staver *et al.*, 2011) and is therefore inferred to be susceptible to climate change. The proportion of trees and grasses in savannas is considered inherently unstable under some conditions (DeMichele *et al.*, 2011; Staver *et al.*, 2011; Wake, 2012). Savannas are characterized by annual to decadal fires of relatively low intensity, which are an important factor in maintaining the tree-grass proportions (Beerling and Osborne, 2006), but also constitute a major global source of pyrogenic emissions from land to atmosphere (Schultz *et al.*, 2008; van der Werf *et al.*, 2010). The differential effects of climate change, rising CO_2, fire and herbivory on trees and grasses have the potential to alter the structure, composition and ecosystem service delivery capacity of mixed tree-grass systems (e.g. Hughes *et al.*, 2006). Since tropical savannas occupy about an eighth of the global land surface, and mixed tree-grass systems outside the tropics cover a similar area, small changes in their structure or fire regime can have globally-significant effects on the emission or uptake of radiatively-active gases and particles.

There is evidence from many parts of the world that the tree cover and biomass in savannas has increased over the past century and in some places, on all continents, continues to do so (*high agreement, robust evidence*: Cabral *et al.*, 2009; Angassa and Oba, 2008; Moleele *et al.*, 2002; Wigley *et al.*, 2009; Witt *et al.*, 2009; Lunt *et al.*, 2010; Rohde and Hoffman, 2012). The general consequences are more carbon stored per unit land area as tree biomass and soil organic matter (Hughes *et al.*, 2006; Liao *et al.*, 2006; Knapp *et al.*, 2007; Throop and Archer, 2008; Boutton *et al.*, 2009), changes in hydrology (Muñoz-Robles et al 2011) and reduced grazing potential (Scholes and Archer, 1997). Increasing tree cover in savannas has been attributed to changes in land management (Joubert *et al.*, 2008; Van Auken, 2009), rising CO_2 (Bond and Midgley, 2012; Buitenwerf *et al.*, 2012), climate variability and change (Eamus and Palmer, 2008; Fensham *et al.*, 2009) or two or more of these factors acting in combination (Ward, 2005; Bond *et al.*, 2008). As yet there are no studies that definitively attribute the relative importance of the various causes of woody plant biomass increase in savannas and grasslands, but there is *medium agreement* and *robust evidence* that climate and atmospheric changes are contributing factors in many cases. The increased growth rate of C3 trees relative to C4 grasses under by rising CO_2 could relieve the demographic bottleneck that keeps trees trapped within the flame zone of the grasses, a hypothesis supported by elevated CO_2 experiments with savanna saplings (Kgope *et al.*, 2010). A vegetation model of grasslands, savannas and forests suggests that rising CO_2 does increase the likelihood of abrupt shifts to woodier states, but the transition will take place at different CO_2 concentrations in different environments (Higgins and Scheiter, 2012). On the other hand, observation of contrasts in the degree of savanna thickening between land parcels with the same CO_2 exposure but different land use histories, topographic position or soil depth (Wu and Archer, 2005; Wiegand *et al.*, 2005) imply that land management, water balance and microclimate are also important. Tree cover in savannas is rainfall-constrained (Sankaran *et al.*, 2005), suggesting that increases in rainfall could lead to increased tree biomass. In some places the savanna boundary is moving into former grasslands on elevation or climate gradients (Breshears, 2006).

It has been projected that drying and greater seasonality, acting in conjunction with increased fire, could lead to more savanna-like conditions in parts of the Amazon basin (Malhi *et al.*, 2009a; Box 4-3). In parts of Central Africa, forests have been observed to be moving into adjacent savannas and grasslands (Mitchard *et al.*, 2009), possibly due to depopulation and fire changes. In northern Australia, forest is expanding into former savanna areas (Brook and Bowman, 2006; Tng *et al.*, 2012; Bowman *et al.*, 2011

4.3.3.2.2. Grasslands and shrublands

Much evidence from around the world shows that dry grasslands and shrublands are highly responsive in terms of primary production, species composition and carbon balance to changes in water balance (precipitation and evaporative demand) within the range of projected climate changes (e.g., Sala *et al.*, 1988; Snyman and Fouché, 1993; Fay *et al.*, 2003; Peñuelas *et al.*, 2004, 2007; Prieto *et al.*, 2009; Wu and Chen, 2013) Other factors being equal, grasslands and shrublands are in cool areas are expected to respond to warming with increased primary production, while those in hot areas are expected to show decreased production. Grasslands are exposed to rising CO_2, which is postulated to stimulate plant production, but more so for temperate grasses, herbs and woody plants with a C3 photosynthetic system than for C4 tropical grasses (see section 4.2.4.4). Some grasslands are simultaneously exposed to elevated levels of nitrogen deposition, which alters species composition, increases primary production up to a point and decreases it thereafter (see section 4.2.4.2, Bobbink *et al.*, 2010; Cleland and Harpole, 2010). Most rangelands are subject to grazing and fire. All these factors may have interactive effects, and species composition changes may overwhelm or alter the physiological climate effects (Suttle *et al.*, 2007).

Drawing on published studies, Ravi *et al.* (2010) found that changing climate and land use have resulted in increased aridity and a higher frequency of droughts in drylands around the world. They predict increasing dominance of abiotic controls of land degradation (in contrast to direct human- or herbivore-driven degradation); in particular highlight changes in hydrology and the erosion of soil by wind.

Rainfall amount and timing have large effects on a wide range of biological processes in grasslands and shrublands, including seed germination, seedling establishment, plant growth, flowering time, root mass, community composition, population and community dynamics production, decomposition and respiration, microbial processes and carbon assimilation (e.g. Peñuelas *et al.*, 2004, 2007; Beier *et al.*, 2008; Sowerby *et al.*, 2008; Albert *et al.*, 2011; Albert *et al.*, 2012; Miranda *et al.*, 2009; Selsted *et al.*, 2012; Walter *et al.*, 2012). In a controlled experiment with communities of tallgrass prairie species in Kansas, Fay *et al.* (2008) showed that changes in the interval between rainfall events and the rainfall delivered by individual storms altered carbon assimilation and respiration rates independently of changes in the total amount of water supplied. A similar experiment on a Mediterranean semiarid grassland community (Miranda *et al.*, 2009) found that delayed watering led to decreases in plant productivity and to delayed flowering. Species diversity was not affected by delayed onset of rain; however, it was reduced by changes in the frequency, amount and seasonality of wetting. In the Mongolian steppe (Shinoda *et al.*, 2010), drought reduced the above ground plant mass but did not substantially affect the root mass. A subset of species did not recover to pre-drought levels once precipitation returned to normal levels. A water and temperature manipulation experiment in China indicated that changes in water balance had a stronger effect on grassland microbial processes leading to carbon storage than changes in temperature (Liu *et al.*, 2009). Engler *et al.* (2011) emphasized that precipitation changes were as important for mountain flora in Europe as temperature changes, and the greatest composition changes will probably occur when decreased precipitation accompanies warming. Vohland and Barry (2009) reviewed the effectiveness of in situ rainwater harvesting (RWH) as an adaptation to climate change in sub-Saharan Africa and concluded that it conferred higher food security and income, but may strengthen conflicts between nomadic and sedentary populations.

Experimental manipulation of six European shrublands on a latitudinal gradient showed the response to warming and drought to depend on site, year and plant species (Peñuelas *et al.*, 2004, 2007). Droughts decreased aboveground net primary production two thirds of the sites. Responses to warming were weaker in the presence of aridity. Gao and Giorgi (2008) identified the southern Mediterranean as particularly vulnerable to water stress and desertification processes under climate change conditions. Analyzing 168 site-years of eddy covariance measurements, Wu and Chen (2013) found summer drought to reduce both summer gross primary production and net ecosystem production in grasslands and crops of North America.

A European gradient study (Emmett *et al.*, 2004), showed that N mineralization in shrublands under either arid or wet conditions is more sensitive to periodic droughts than systems under more mesic conditions. An increase in drought frequency, without an increase in drought severity, leads to loss of soil carbon in moist, carbon-rich moorlands, due to changes in soil structure or soil microbial community leading to increased hydrophobicity and soil respiration (Sowerby *et al.*, 2008, 2010). Responses of shrublands to drought may partly be driven by changes in the soil microbial community (Jensen *et al.*, 2003) or changes in soil fauna (Maraldo *et al.*, 2008).

Beier *et al.* (2008) found that nitrogen limitation reduces acclimation in plant production, as a result of an asymmetrical response to warming between the carbon and nitrogen cycles. Decreased tissue concentrations of phosphorus was also associated with warming and drought (Peñuelas *et al.*, 2004; Beier *et al.*, 2008; Peñuelas *et al.*, 2012). strong interactions of warming with disturbances have been observed leading to increased nitrogen leaching from shrubland ecosystems (Beier *et al.*, 2004).

N fertilization and nighttime warming caused soil and plant community responses within one season in a Chihuahuan semi-arid desert (Collins *et al.*, 2010). In contrast, Grime *et al.* (2008) found little species composition change after 13 years of manipulation of water and temperature in an infertile grassland in England. The community composition of subalpine grasslands in Switzerland have changed relatively little over the past fifty years (Vittoz *et al.*, 2009). The changes that did occur were largely associated with changes in land management rather than climate, although they were consistent with warming trends.

Sommer *et al.* (2010) used global empirical relationships between plant species richness and climate variables such as temperature, moisture and radiation to project richness changes under future climates. This method is independent of the usual species-by-species or biome-based climate niche approach, but its predictions apply to the long-term equilibrium outcome, rather than changes in the next few decades. In most temperate and arctic regions, the capacity to support richer (i.e. more diverse) communities increases with rising temperature, while the projections indicate a strong decline in capacity to support species-rich communities in most tropical and subtropical regions.

Many grasslands, shrublands and savannas are characterized by relatively frequent but low-intensity fires. The fire frequency, intensity and seasonality in southern Africa are primarily under climate control, and secondarily influenced by management (Archibald *et al.*, 2009). In South America, El Niño-Southern Oscillation climate modes strongly influence on area burned in Colombian grasslands (Armenteras-Pascual *et al.*, 2011). Fire frequency in grasslands and forests in Australia is projected to increase, due to climate change (Pitman *et al.*, 2007). Since it is well-established that plant species composition is sensitive to the fire regime (e.g. Gibson and Hulbert, 1987; Uys *et al.*, 2004; Gill *et al.*, 1999 and many other studies) this provides an indirect mechanism by which climate change can lead to species composition change in grasslands and rangelands.

Relatively little is known regarding the combined effect of climate change, other global change factors and increasing use pressure by large mammal herbivores in rangelands, nor on the consequences for pastoral livelihoods that depend on rangelands (Thornton *et al.*, 2009).

4.3.3.2.3. Deserts

The deserts of the world, defined as land areas with an arid or hyperarid climate regime, occupy 35 % of the global land surface. Deserts are sparsely populated, but the people who do live there are amongst the poorest in the world (Millennium Ecosystem Assessment, 2005b). There is *medium agreement* but *limited evidence* that the present extent of deserts will increase in the coming decades, despite the projected increase in rainfall at a global scale, as a result of the strengthening of the Hadley circulation. The descending air on the poleward side of the Hadley circulation results in decreased rainfall (Mitas and Clement, 2005; Seidel *et al.*, 2008; Johanson and Fu, 2009; Lu *et al.*, 2009; Zhou *et al.*, 2011) and which determines the location of the broad band of warm deserts lands approximately 15-30° N and S of the equator. Recent satellite data show a greening trend in the Sahel, associated with a return to wetter climates following a multidecade dry spell. There may be a feedback to the global climate from an increase in desert extent (Alkama *et al.*, 2012), which differs in sign between deserts closer to the equator than 20° and those closer to the poles. In model simulations, extension of the ‘warm deserts’ causes warming, while extension of the ‘cold deserts’ causes cooling, in both cases largely through albedo-mediated effects. Two special circumstances of desert areas are important with respect to climate change. Deserts are expected to become warmer and drier at faster rates than other terrestrial regions (Lapola *et al.*, 2009). Most deserts are already extremely hot, and therefore further warming will probably be physiologically injurious rather than beneficial. Secondly, the ecological dynamics in deserts are rainfall event-driven (Holmgren *et al.*, 2006), often involving the concatenation of a number of quasi-independent events. According to a conceptual model elaborated by Lapola *et al.* (2009) some desert tolerance mechanisms (e.g., biological adaptations by long-lived taxa) may be outpaced by global climate change.

Deserts are expected to become warmer and drier at a faster rate than other terrestrial regions (Stahlschmidt *et al.*, 2011). The warm deserts are already extremely hot, and therefore further warming is generally physiologically injurious rather than beneficial. Ecological dynamics in deserts are rainfall event-driven (Holmgren *et al.*, 2006), often involving the concatenation of a number of quasi-independent events. According to a conceptual model elaborated by Stahlschmidt *et al.* (2011) some desert tolerance mechanisms (e.g., biological adaptations by long-lived taxa) may be outpaced by global climate change.

4.3.3.3. Rivers, Lakes, Wetlands and Peatlands

Freshwater ecosystems are considered to be among the most threatened on the planet (Dudgeon *et al.*, 2006; Vörösmarty *et al.*, 2010). Fragmentation of rivers by dams and the alteration of natural flow regimes have led to major impacts on freshwater biota (Pringle, 2001, Bunn and Arthington, 2002; Nilsson *et al.*, 2005). Floodplains and wetland areas have become occupied for intensive urban and agricultural land use to the extent that many are functionally extinct from their rivers (Tockner *et al.*, 2008). Pollution from cities and agriculture, especially nutrient loading, has resulted in declines in water quality and the loss of essential ecosystem services (Allan, 2004). As a direct consequence of these and other impacts, freshwater systems have the highest rates of extinction of any ecosystem (as much as 4% pa for some groups - e.g. crayfish, mussels, fishes and amphibians in North America), with estimates that at least 10,000-20,000 freshwater species are extinct or at risk (Strayer and Dudgeon, 2010). This is particularly significant considering that freshwater habitats support 6% of all described species, including approximately 40% of fish diversity and a third of the vertebrate diversity (Dudgeon *et al.*, 2006; Balian *et al.*, 2008).

Peatlands contain large stocks of carbon that are vulnerable to change through land use and climate change. Although peatlands cover only about 3% of the land surface, they hold the equivalent of half of the atmosphere's carbon (as CO_2), or one third of the world's soil carbon stock (Limpens *et al.*, 2008; Page *et al.*, 2011). About 14-20% of the world's peatlands are currently used for agriculture (Oleszczuk *et al.*, 2008) and many, particularly peat swamp forests in Southeast Asia, are still undergoing major transformations through drainage and burning in preparation for oil palm and other crops or through unintentional burning (Limpens *et al.*, 2008; Hooijer *et al.*, 2010). Deforestation, drainage, and burning in Indonesian peat swamp forests can release 1,400 Mg CO_2 ha^{-1} (Murdiyarso *et al.*, 2010), contributing significantly to global GHG emissions, especially during periods of intense drought associated with ENSO when burning is more common (Page *et al.*, 2002). Anthropogenic disturbance has changed peatlands from being a weak global carbon sink to a source (Frolking *et al.*, 2011) with large inter-annual variability.

It is *very likely* that these stressors to freshwater ecosystems and peatlands will continue to dominate as human demand for water resources grows, accompanied by increased urbanization and intensification of agriculture (Vörösmarty *et al.*, 2000; Malmqvist *et al.*, 2007; Dise, 2009). However, climate change will have significant additional impacts on freshwater ecosystems (*high confidence*), from altered thermal regimes, altered precipitation and flow regimes and, in the case of coastal wetlands, sea level rise. Specific aquatic habitats that are most vulnerable to these direct climate effects, especially rising temperatures, are those at high altitude and high latitude, including arctic and subarctic bog communities on permafrost, and alpine and arctic streams and lakes (see 4.3.4.4; Smith *et al.*, 2005; Smol and Douglas, 2007a). It is noteworthy that these high latitude systems currently experience a relatively low level of threat from other human activities (Vörösmarty *et al.*, 2010). Dryland rivers and wetlands, many already experiencing severe water stress from human consumptive use, are also *likely* to be further impacted by decreased and more variable precipitation and higher temperatures. Headwater stream systems in general are also vulnerable to the effects of warming because their temperature regimes closely track air temperatures (Caissie, 2006).

Evidence of rising stream and river temperatures over the past few decades across several continents continues to grow (Chessman, 2009; Kaushal *et al.*, 2010; Langan *et al.*, 2001; Morrison *et al.*, 2002; Ormerod, 2009; van Vliet *et al.*, 2011; Webb and Nobilis, 2007), and has been linked by observational and experimental studies to shifts in invertebrate community composition, including declines in cold sternothermic species (Brown *et al.*, 2007; Chessman, 2009; Durance and Ormerod, 2007; Ormerod, 2009). Rising water temperatures are also implicated in changes in the composition of river fish communities (Buisson *et al.*, 2008; Daufresne and Boet, 2007), especially in headwater streams where species are more sensitive to warming (e.g. Buisson and Grenouillet, 2009), and this will probably restrict the distribution of cool-water species such as salmonids within their current range (Bartholow, 2005; Bryant, 2009; Ficke *et al.*, 2007; Hague *et al.*, 2011). While these changes in river temperature regimes may also open up new habitat at higher latitudes (or altitudes) for migratory (Reist *et al.*, 2006) and cool- and warm water species of fish (Tisseuil *et al.*, 2012), there is *high confidence* that range contraction threatens the long term persistence of some fully aquatic species, including mountain-top endemics; e.g. species of spiny crayfish (Parastacidae: *Eustacus*) in eastern Australia (Ponniah and Hughes, 2004).

The surface and epilimnetic waters in many lakes also show increases in temperature over the past four decades, with warming trends detected in North America, Eurasia and Africa (Adrian *et al.*, 2009). Rising temperatures resulting in early onset and increased duration and stability of the thermocline in temperate lakes during summer (Winder and Schindler, 2004) are projected to favor a shift in dominance to smaller phytoplankton (Parker *et al.*, 2008; Yvon-Durocher *et al.*, 2011) and cyanobacteria (Johnk *et al.*, 2008; Paerl *et al.*, 2011; Wiedner *et al.*, 2007), especially in those ecosystems experiencing high anthropogenic loading of nutrients (Wagner and Adrian, 2009);

with impacts to water quality, food webs and productivity (Gyllström *et al.*, 2005; O'Reilly *et al.*, 2003; Parker *et al.*, 2008; Shimoda *et al.*, 2011; Verburg *et al.*, 2003). Emergent aquatic macrophytes are likely to expand their northward distribution and percentage cover in boreal lakes and wetlands, posing an increasing overgrowth risk for sensitive macrophyte species (Alahuhta *et al.*, 2011). Long-term shifts in macroinvertebrate communities have also been observed in European lakes where temperatures have increased (Burgmer *et al.*, 2007), noting that warming may increase species richness in smaller temperate waterbodies, especially those at high altitude (Rosset *et al.*, 2010). While less studied, it has been proposed that tropical ectotherms will be particularly vulnerable because they will approach critical maximum temperatures proportionately faster than species in high latitude environments, despite lower rates of warming (Deutsch *et al.*, 2008; Hamilton, 2010; Laurance *et al.*, 2011).

There is growing evidence that climate induced changes in precipitation will significantly alter ecologically important attributes of hydrologic regimes in rivers and wetlands, and exacerbate impacts from human water use in developed river basins (see Box CC-RF; Aldous *et al.*, 2011; Xenopoulos *et al.*, 2005). Freshwater ecosystems in Mediterranean-montane ecoregions (e.g. Australia, California and South Africa), are projected to experience a shortened wet season and prolonged, warmer summer season (Klausmeyer and Shaw, 2009), increasing the vulnerability of fish communities to drought (Magalhães *et al.*, 2007; Hermoso and Clavero, 2011) and floods (Meyers *et al.*, 2010). Shifts in hydrologic regimes in snow-melt systems, including earlier runoff and declining base flows in summer (Stewart *et al.*, 2005; Stewart, 2009), are projected to impact on freshwater ecosystems, through changes in physical habitat and water quality (Bryant, 2009). Declining rainfall and increased inter-annual variability will probably increase low-flow and dry-spell duration in dryland regions, leading to reduced water quality in remnant pools (Dahm *et al.*, 2003), reduction in floodplain egg- and seed-banks (Capon, 2007; Jenkins and Boulton, 2007), the loss of permanent aquatic refugia for fully aquatic species and water birds (Bond *et al.*, 2008; Johnson *et al.*, 2005; Sheldon *et al.*, 2010), and terrestrialization of wetlands (Davis and Thompson, 2010).

Climate induced changes in precipitation will probably be an important factor altering peatland vegetation in temperate and boreal regions, with decreasing wetness during the growing season generally associated with a shift from a *Sphagnum* dominated to vascular plant dominated vegetation type and a general decline of C sequestration in the longer term (Limpens *et al.*, 2008). Mire ecosystems (i.e. bogs, transition bogs and fens) in central Europe face severe climate risk, with increased summer temperatures being particularly important (Essl *et al.*, 2012). Declines in precipitation and longer dry seasons in major tropical peatland areas in southeast Asia, are projected to result in lower water tables more often and for longer periods, with an increased risk of fire (Li *et al.*, 2007; Rieley *et al.*, 2008; Frolking *et al.*, 2011).

Sea level rise will lead to direct losses of coastal wetlands with associated impacts on waterbirds and other wildlife species dependent on fresh water (BMT WBM, 2010; Pearlstine *et al.*, 2010; Traill *et al.*, 2010) but the impact will probably be relatively small compared with the degree of direct and indirect human-induced destruction (Nicholls, 2004). River deltas and associated wetlands are particularly vulnerable to rising sea level, and this threat is further compounded by trapping of sediment in reservoirs upstream and subsidence from removal of oil, gas and water (Syvitski *et al.*, 2009; see Chapter 5.3.1.4). Lower river flows might exacerbate the impact of sea level rise and thus salinization on freshwater ecosystems close to the ocean (Ficke *et al.*, 2007).

4.3.3.4. Tundra, Alpine, Permafrost Systems

The region of the High Arctic, and its tundra-dominated landscapes, has warmed more than the global average over the last century (Kaufman *et al.*, 2009; Hartmann *et al.*, in press. Changes consistent with warming are also evident in the freshwater systems, ecosystems (both plants and animals) and permafrost of the region (Hinzman *et al.*, 2005; Axford *et al.*, 2009; Jia *et al.*, 2009b; Post *et al.*, 2009; Prowse and Brown, 2010; Romanovsky *et al.*, 2010; Walker *et al.*, 2012). Change is widespread , with most of the Arctic experiencing recent change in vegetation photosynthetic capacity and other aspects, particularly in areas adjacent to areas of the Arctic with rapidly retreating sea ice (Bhatt *et al.*, 2010).

There is *high confidence* that continued climate change is projected to cause the terrestrial vegetation and lake systems of the Arctic to change substantially in the future, with an ongoing expansion in woody vegetation cover projected in tundra regions over the 21st Century in the CMIP5 Earth System Models (Ciais *et al.*, in press) by dynamic global vegetation models driven by other climate model projections, and by observationally-based statistical models (Pearson *et al.*, 2013). Changes may be complex (see Box 4-4) and in some cases involve non-linear and threshold responses to warming and other climatic change (Hinzman *et al.*, 2005; Mueller *et al.*, 2009b; Bonfils *et al.*, 2012). Due to long response times of vegetation to both warming and increased CO_2 (Ciais *et al.*, in press; Falloon *et al.*, 2012) Earth System Models project Arctic vegetation change to continue long after any stabilization of global mean temperature. In some regions, reduced surface albedo due to increased vegetation cover is projected to cause further local warming even in scenarios of stabilized global radiative forcing due to greenhouse gases (Falloon *et al.*, 2012).

In the arctic tundra biome, vegetation productivity has systematically increased over the past few decades, as documented across a range of scales in both North America and northern Eurasia – from the plot level (Myers-Smith *et al.*, 2011; Elmendorf *et al.*, 2012) to the region (Stow *et al.*, 2007) to continental (Jia *et al.*, 2009b) and the circumpolar arctic (Goetz *et al.*, 2007; de Jong *et al.*, 2011). This phenomenon is amplified by retreat of coastal sea ice (Bhatt *et al.*, 2010) and has been widely discussed in the context of increased shrub growth consistent with documented shrub expansion over the last half century through repeat photography and satellite observations (Forbes *et al.*, 2010; Myers-Smith *et al.*, 2011). Deciduous shrubs (i.e., dwarf birch, alder and willow species), in particular, respond to warming with increased growth (Euskirchen *et al.*, 2009; Lantz *et al.*, 2010), but this response is shared with other plant functional types, particularly graminoids (Walker, 2006; Epstein, 2008). Analyses of satellite time series data show the increased productivity trend is not unique to shrub-dominated areas (Jia *et al.*, 2009b; Beck and Goetz, 2011), thus greening is a response shared by multiple vegetation communities and continued changes in the tundra biome can be expected irrespective of shrub presence. Shrub expansion and height changes remain particularly important, however, because they trap snow, mediate winter soil temperature and summer moisture regimes, increase nutrient mineralization, and produce a positive feedback for additional shrub growth (Sturm *et al.*, 2005; Lawrence *et al.*, 2007; Bonfils *et al.*, 2012). Although increased shrub cover and height produce shadowing that reduce ground heat flux and active layer depth, they also reduce surface albedo, increase energy absorption and evapotranspiration (Chapin III *et al.*, 2005; Blok *et al.*, 2010), and produce feedbacks that reinforce shrub densification and regional warming (Lawrence and Swenson, 2011; Bonfils *et al.*, 2012). On balance, these feedbacks can act to partially offset one another, but when coupled with warmer and wetter conditions they act to increase active layer depth and permafrost thaw (Yi *et al.*, 2007; Bonfils *et al.*, 2012).

The arctic tundra biome is also experiencing shifts in two additional phenomena; fire disturbance and permafrost degradation. Both of these processes facilitate conditions for woody species establishment in tundra areas, either through incremental migration or via more rapid “leap-frogging” to areas reinitialized by burning (Epstein *et al.*, 2007; Goetz *et al.*, 2011). When already present at the boreal-tundra ecotone, even sparsely, shrub and tree species show increased productivity with warmer conditions (Devi *et al.*, 2008; Andreu-Hayles *et al.*, 2011; Elmendorf *et al.*, 2012). Tundra fires not only emit large quantities of combusted carbon formerly stored in vegetation and organic soils (Mack *et al.*, 2011; Rocha and Shaver, 2011) but also increase active layer depth during summer months (Racine *et al.*, 2004; Liljedahl *et al.*, 2007) and produce thermokarsting associated with thawing of ice-rich permafrost. There is tremendous variability in the degree of thermokarsting associated with fire disturbance, depending upon the substrate and ice content (Jorgenson *et al.*, 2010) but the combination of thermokarsting and seasonal cryoturbation create conditions that alter vegetation succession (Racine *et al.*, 2004; Lantz *et al.*, 2009; Higuera *et al.*, 2011).

There is *high confidence* that the area of permafrost is projected to continue to decline over the first half of the 21st Century in all emissions scenarios (Figure 4-11). In the RCP2.6 scenario of an early stabilization of CO_2 concentrations, permafrost area is projected to stabilize at a level approximately 20% below the 20th Century area, and then begin a slight recovering trend. In RCP4.5, in which CO_2 concentration is stabilized at approximately 550ppmv by the mid-21st Century, permafrost continues to decline for at least another 250 years. In the RCP8.5 scenario of ongoing CO_2 rise, permafrost area is simulated to approach zero by the middle of the 22nd Century (Figure 4-11).

[INSERT FIGURE 4-11 HERE
Figure 4-11: Simulations of past and future (for three Representative Concentration Pathways - RCPs) northern hemisphere permafrost area with a maximum thaw depth less than 3m deep (Caesar *et al.*, 2012) using the HadGEM2-ES Earth System Model (Jones *et al.*, 2011).]

Frozen soils and permafrost currently hold more than twice the carbon than the atmosphere and thus represent a particularly large vulnerability to climate change (i.e., warming). Although the Arctic is currently a net carbon sink, continued warming will act to soon turn the Arctic to a net carbon source, that will in turn create a potentially strong positive feedback to accelerate Arctic (and global) warming with additional releases of CO_2, CH_4, and perhaps N_2O, from the terrestrial biosphere into the atmosphere (Schuur *et al.*, 2008; Schuur *et al.*, 2009; Maslin *et al.*, 2010; McGuire *et al.*, 2010; O'Connor *et al.*, 2010; Schaefer *et al.*, 2011). Moreover, this feedback is already accelerating due to climate-induced increases in fire (McGuire *et al.*, 2010; O'Donnell *et al.*, 2011). The rapid retreat of snowcover, and resulting spread of shrubs and trees into areas currently dominated by tundra has also already begun, and will continue to serve as a positive feedback accelerating high latitude warming (Chapin III *et al.*, 2005; Bonfils *et al.*, 2012).

There is *medium confidence* that rapid change in the Arctic is also affecting its animals. For example, seven of 19 sub-populations of the polar bear are declining in number, while four are stable, one is increasing and the remaining seven have insufficient data to identify a trend (Vongraven and Richardson, 2011). Declines of two of the sub-populations are linked to reductions in sea ice (Vongraven and Richardson, 2011). Polar bear populations are projected to decline greatly in response to continued Arctic warming (Hunter *et al.*, 2010), and it is expected that the populations of other Arctic animals (e.g., fox and caribou) will be affected dramatically by climate change (Post *et al.*, 2009; Sharma *et al.*, 2009). Simple niche-based, or climatic envelope models have difficulty in capturing the full complexity of these future changes (MacDonald, 2010).

There is *high confidence* that alpine systems are already showing a high sensitivity to on-going climate change and will be highly vulnerable to change in the future. In western North America, warming, glacier retreat, snowpack decline and drying of soils is already causing a large increase in mountain forest mortality, wildfire and other ecosystem impacts (e.g., Westerling *et al.*, 2006; Kelly and Goulden, 2008; Crimmins *et al.*, 2009; van Mantgem *et al.*, 2009; Pederson *et al.*, 2010; Muhlfeld *et al.*, 2011; Schwilk and Keeley, 2012; Park Williams *et al.*, 2012), and disturbance will continue to be an important agent of climate-induced change in this region (Littell *et al.*, 2010). Alpine ecosystems already appear to already be changing in response to climate change in Africa, Tibet, the Alps, the tropics and elsewhere (Cannone *et al.*, 2007, 2008; Lenoir *et al.*, 2008, 2010; Cui and Graf, 2009; Britton *et al.*, 2009; Normand *et al.*, 2009; Chen *et al.*, 2009, 2011; Allen *et al.*, 2010a; Eggermont *et al.*, 2010; Kudo *et al.*, 2011; Laurance *et al.*, 2011; Engler *et al.*, 2011; Dullinger *et al.*, 2012). For example, in a study of permanent plots from 1994 to 2004 in the Austrian high Alps, a range contraction of subnival to nival vascular plant species was indicated at the downslope edge, and an expansion of alpine pioneer species at the upslope edge (Pauli *et al.*, 2007). Thermophilous vascular plant species were observed to colonize in alpine mountain-top vegetation across Europe during the past decade (Gottfried *et al.*, 2012). As with the Arctic, permafrost thawing in alpine systems could provide a strong positive feedback in those systems (e.g., Tibet; Cui and Graf, 2009).

_____ START BOX 4-4 HERE _____

Box 4-4. Boreal – Tundra Biome Shift

Changes in a suite of ecological processes currently underway across the broader arctic region are consistent with earth system model predictions of climate-induced geographic shifts in the range extent and functioning of the tundra and boreal forest biomes (Figure 4-12). Thus far these changes appear to be not so much threshold responses as gradual and systematic shifts across temperature and moisture gradients. Responses are expressed through gross and net primary production, microbial respiration, fire and insect disturbance, vegetation composition, species range expansion and contraction, surface energy balance and hydrology, active layer depth and permafrost thaw, and a range of other inter-related variables. Because the high northern latitudes are warming more rapidly than other parts of the earth, due at least in part to arctic amplification (Serreze and Francis, 2006), the rate of change in these ecological processes are sufficiently rapid that they can be documented *in situ* (Hinzman *et al.*, 2005; Post *et al.*, 2009; Peng *et al.*, 2011; Elmendorf *et al.*, 2012) as well as from satellite observations (Goetz *et al.*, 2007; Beck *et al.*, 2011b; Xu *et al.*, 2013) and captured in earth system models (McGuire *et al.*, 2010).

Gradual changes in composition resulting from decreased evergreen conifer productivity and increased mortality, as well as increased deciduous species productivity, are facilitated by more rapid shifts associated with fire disturbance (Mack *et al.*, 2008; Johnstone *et al.*, 2010). Each of these interacting processes, as well as insect disturbance and associated tree mortality, are tightly coupled with warming-induced drought (Ma *et al.*, 2012; Anderegg *et al.*, 2013a; Choat *et al.*, 2012). Similarly, gradual productivity increases at the boreal-tundra ecotone are facilitated by leap-frog dispersal into areas disturbed by tundra fire and thermokarsting (Tchebakova *et al.*, 2009; Hampe, 2011; Brown, 2010). In North America these coupled interactions set the stage for changes in ecological processes, already documented, consistent with a biome shift characterized by increased deciduous composition in the interior boreal forest and evergreen conifer migration into tundra areas that are, at the same time, experiencing increased shrub densification. The net feedback of these ecological changes to climate is multi-faceted, complex, and not yet well known across large regions except via modeling studies, which are often poorly constrained by observations.

[INSERT FIGURE 4-12 HERE
Figure 4-12: Tundra-Boreal Biome Shift. Earth system models predict a northward shift of Arctic vegetation with climate warming, as the boreal biome migrates poleward into what is currently tundra. Observations of shrub expansion in tundra, increased tree growth at the tundra-forest transition, and tree mortality at the southern extent of the boreal forest in recent decades are consistent with model projections. Vegetation changes associated with a biome shift, which is facilitated by intensification of the fire regime, will modify surface energy budgets and net ecosystem carbon balance. Arrows indicate the magnitude of albedo and net ecosystem carbon balance (NECB) for boreal forest and tundra biomes, and albedo for sea ice and open water.]

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4.3.3.5. Highly Human-Modified Systems - Plantations, Bioenergy Systems, Urban Ecosystems, Cultural Landscapes

As the majority of ice-free land surface is dominated by highly human modified systems, we assess their vulnerability to climate change particularly for those systems not dealt with elsewhere, i.e. except agriculture (WGII, chapter 7) and fisheries (WGII, chapter 3).

4.3.3.5.1. Plantation forestry

While a majority of general aspects on forests are already dealt with in section 4.3.3.1, here we focus on issues that are specifically relevant to plantation forests. Forest plantations are established through afforestation of recent non-forest land and reforestation of forest land, often with tree crop replacement (Dohrenbusch and Bolte, 2007; FAO, 2010b). With 7%, they currently cover only a minor fraction of the global forest area, and the largest plantation areas exist in Asia, Europe (excl. Russian Federation) and North and South America (FAO, 2010a). However, the area of forest plantations has grown rapidly by about five million ha from 2000 to 2010 (FAO, 2010b). Most recent plantations have been established in the tropics and subtropics, but also in some temperate regions, in particular in China (Kirilenko and Sedjo, 2007; FAO, 2010a), mostly by afforestation of non-forest area (FAO, 2010b).

In most areas with forest plantations, forest growth rates have generally increased during the last decades - in Europe also because of formally more intensive harvesting (Ciais *et al.*, 2008; Lindner *et al.*, 2010), but the variability is large, and in some areas production has decreased (see 4.3.3.1). In forests that are not highly water-limited, these trends are consistent with higher temperatures and extended growing seasons, but, as in the case of forests in general, clear attribution is difficult because many environmental drivers and changes in forest management interact (*e.g*. Boisvenue and Running, 2006; Ciais *et al.*, 2008; Dale *et al.*, 2010; see also 4.3.3.1).

Regarding future climatically driven changes, results from several studies with forest yield models suggest increases in forest production (Kirilenko and Sedjo, 2007), but these results may be overly optimistic because many models may overestimate potential positive effects of elevated CO_2 (Kirilenko and Sedjo, 2007; see 4.2.4.4) and the effects of disturbances, such as wildfires, forest pests, pathogens and windstorms, which are major drivers of forest dynamics, are often either poorly or not at all represented (Kirilenko and Sedjo, 2007). Using a model that accounts for fire effects and insect damage, Kurz *et al.* (2008), for example, showed that recent insect outbreaks might have caused a transition in the Canadian forest sector from a sink to a source of carbon. Future projections for particular stands or regions are also uncertain because results from different models often differ substantially, both regarding forest productivity (*e.g*. Sitch *et al.*, 2008; Keenan *et al.*, 2011) and potential species ranges (see 4.3.3.1.2). Nevertheless, decreased production is expected in particular in already dry forest regions for which further drying is projected, such as the south-western U.S. (Williams *et al.*, 2010a), and extreme drying might also decrease forest yields in currently not water-limited forests (*e.g.* Sitch *et al.*, 2008; see 4.3.3.1). Plantations in cold-limited areas could benefit from climate change and their productivity could increase if associated changes in disturbances, pests and pathogens do not outweigh the potential positive climatic effects.

Many plantation forests are monospecies stands or sometimes even include only a limited number of clones of one species. In the temperate and boreal zone, native species are commonly used (but in some cases beyond their native range), while in the tropics, conventional tree planting is mainly based on exotic species from a few genera such as *Pinus*, *Eucalyptus* and *Acacia* grown in single-species stands. Low species (and often also genetic) diversity compared with natural stands might render plantation forests particularly vulnerable to climate change (*e.g*. Hemery, 2008). Choosing provenances that are well adapted to current and future climates is extremely difficult because of uncertainties in climate projections (Broadmeadow *et al.*, 2005). Furthermore, it is highly uncertain how forest pests and pathogens will spread as a result of climate change and trade and new pathogen-tree interactions might occur (e.g. Brasier and Webber, 2010). Nevertheless, adaptive forest management can decrease the vulnerability of plantations to climate change (Hemery, 2008; Bolte *et al.*, 2009; Seppälä, 2009; Dale *et al.*, 2010. For example, risk spreading by promoting multi-species mixed stands and natural regeneration, which can increase genetic diversity (Kramer *et al.*, 2010), has been advocated as a plausible adaptation strategy for temperate forests (Hemery, 2008; Bolte *et al.*, 2010). Also in the tropics, recent approaches highlight the use of native species in mixed stands (Erskine *et al.*, 2006; Petit and Montagnini, 2006; Hall *et al.*, 2011), but missing information on the ecology of many of the tropical tree species and little experience in managing mixed tropical tree plantations remains to be a major problem (Hall *et al.*, 2011). At least at the southern border of cold-adapted species, such as Norway spruce (*Picea abies*) in Europe, climate change will *very likely* lead to a shift in the main tree species used for forest plantations (Iverson *et al.*, 2008; Bolte *et al.*, 2010).

4.3.3.5.2. Bioenergy systems

Bioenergy sources include traditional forms such as wood and charcoal and more modern forms such as the industrial burning of biomass wastes, the production of ethanol and biodiesel. While traditional biofuels have been in general decline as users switch to fossil fuels or electricity, they remain dominant energy sources in many less-developed parts of the world, such as Africa, and retain a niche in developed countries. The production of modern bioenergy is growing rapidly throughout the world in response to climate mitigation policies that incentivise their use, or as a strategy to decrease oil dependence and thus increase energy security (Cochrane and Barber, 2009). The WG III chapter on energy addresses their potential as a climate mitigation strategy, while the sensitivity of biofuel crops to climate change should be quite similar to those previously mentioned for plantation forestry (which to a large extent are grown for bioenergy purposes) and/or agricultural systems (WGII, chapter 7). In a review on climate change impacts on biofuel yields in temperate environments (Luckman and Kavanagh, 2000) it was concluded that elevated CO_2 might contribute to increase drought tolerance of bioenergy crops (as it is paralleled by improved plant water use), which may lead to constantly high yields. Generally, potentials of bioenergy production under climate change might be high, but are very uncertain (Ma and Zhou, 2012).

An important part to deal with here is the ecosystem impacts of large-scale land-use changes related to the growing of bioenergy biofuels. Policy shifts in OECD countries favor the expansion of biofuel production, sometimes at the expense of food crop production, and placing new pressures on terrestrial and freshwater ecosystems (Searchinger *et* *al.*, 2008; Lapola *et al.*, 2010). It is, for example, unclear if the global trend to reduced forest loss will continue - there are substantial pressures to deforest for the production of food and biofuels (Wise *et al.*, 2009; Meyfroidt and Lambin, 2011). Moiseyev *et al.*, (2011) found that in a 20 years perspective it is very little difference between the IPCC scenarios A1 and B2 regarding harvest level in Europe, and that the EU RES policy may only moderately influence the EU forestry and forest industries as long as the wood price paid by the bioenergy producers are below 50-60 US$ per m^3 wood. Under the assumption of doubling the growth rate of demand for bioenergy until 2030, a scenario by Martin *et al.* (2010) would lead to severe consequences for the global forest sector with a global reduction of forest stocks of 2 % or a 4% reduction for Asia.

Bioenergy potentials are strongly influenced by human food requirements (incl. feed required for livestock), thus integrated approaches to optimize food and bioenergy are needed (Ma and Zhou, 2012). Such considerations ignore areas for the conservation of biodiversity and ecosystems. These are more explicitly dealt with by McAlpine *et al.* (2009) and Millar *et al.* (2004), while in both papers the usage of abandoned land, which was previously under agricultural use, is regarded as an option for biomass production which reduces net warming. However, this ignores for example that such habitats may be core elements in cultural landscapes of high conservation value (many species rich grasslands in Europe have been croplands before and later abandoned), and that the productivity of such areas could be too limited for biofuels (Mishra *et al.*, 2010). As an alternative, Fargione (2011) discusses biofuel crop yield increases on existing cropland, with the aim to avoid expansion of agriculture.

4.3.3.5.3. Cultural landscapes

“Cultural landscapes are at the interface between nature and culture, tangible and intangible heritage, biological and cultural diversity—they represent a closely woven net of relationships, the essence of culture and people’s identity” (Rössler, 2006, p. 334). They are characterized by a long history of human-nature interactions, where man is the main driver and has often created open landscapes, rich in structures and often also in species. A UNESCO Flagship programme focusses especially on cultural landscapes (Rössler, 2006). These landscapes nowadays are often about to lose their roles as recreational species rich entities due to agricultural intensification and extensification (Huntington *et al.*, 2012). Well researched examples are grassland or mixed agriculture landscapes in Europe or rice landscapes in Asia (Kuldna *et al.*, 2009), while such landscapes may well exist across the globe (e.g., Rössler, 2006; Heckenberger *et al.*, 2007).

In such landscapes, conservation efforts - as all across the globe - often focus on the conservation of ecosystems that contain endangered biotic communities. However, in such cultural landscapes this aim might be hard to achieve due to the very dynamic nature of systems. Keeping species in a favorable conservation status in cultural landscapes (one aim e.g. of European policies; EU Council, 1992), can normally only be achieved through appropriate management, as the vast majority of endangered species in the wider countryside depend on certain types of land use for their survival. This requires profound knowledge of the systems and species involved, and as this is rarely the case, conservation success was limited (see Kirdyanov *et al.*, 2012 for a notable exception).

As in many other cases, population and niche models are available and partly already validated (Kirdyanov *et al.*, 2012). This shows where future challenges are to be found: particularly in the quantification of relative importance of climate change in comparison with the habitat and its management (Settele and Kühn, 2009). So far the majority of changes can be attributed to land use as the most obvious driver (Nowicki *et al.*, 2007), while the impact of climate change can be readily detected in few examples (Devictor *et al.*, 2012), combined effects seem to better explain the overall picture (Schweiger *et al.*, 2008; Schweiger *et al.*, 2012), where attribution to climate change seems low to medium. As a consequence, it has been suggested to adjust the European Natura 2000 protected area network to take into account changing climatic conditions and to enable migration or dispersal of species across the landscape (Heubes *et al.*, 2011; Jin *et al.*, 2010).

4.3.3.5.4. Urban ecosystems

Over half of humanity lives in urban areas (see for definition in chapter 8) with a yearly increase of ca. 74 million people (United Nations *et al.*, 2012). Although urban areas cover only ca. 0.5 % of Earth's terrestrial surface (Schneider *et al.*, 2009) they harbor a large variety of species (McKinney, 2008). Urban areas are themselves drivers of climatic change as they are accounted for a significant proportion of total anthropogenic greenhouse gas emissions (Satterthwaite, 2008) and many urban centers are also heavily impacted by increased minimum and sometimes decreased maximum air temperatures, reduced or increased precipitation and altered biogeochemical cycles (Grimm *et al.*, 2008). An important threat to cities comes from extreme events. Many cities are located at coasts or rivers. However since there is *medium confidence* (based on physical conditions) that projected increases in heavy rainfall events would contribute to increases in local flooding (IPCC, 2012) there is *limited evidence* that urban areas will be over-proportionally affected by floods in the future, however, it is *very likely* that sea level will contribute to rise in future and hence affect coastal urban areas (IPCC, 2012). For the future it is *virtually certain* that the frequency and magnitude of warm days and nights (heat waves) will increase globally (IPCC, 2012). However Leonelli *et al.* (2011) projected with the integration of an urban land-surface model in the HadAM3 Global Climate Model a significant higher increase in the frequency of hot nights in urban areas compared to rural areas. Hence also the social aspects in urban areas (health status, outdoor activities) and urban infrastructures will be increasingly affected (IPCC, 2012). There is *high agreement* among scientists that urban climate effects (e.g., increased temperatures) nowadays are similar to projected changes of climatic variables at a local scale. Similar to all other ecosystems, ecological impacts of changing climatic factors in urban ecosystems will change species compositions as well as compositions of traits. Knapp *et al.* (2008b) found that traits compositions of urban plant communities are changing during urbanization towards adaptive characteristics of dry and warm environments. With increasing temperatures, this effect might to continue also in the future and will hence be exacerbated compared to non-urban surroundings. Urban areas are one of the main starting points for the establishment and dispersal of alien species (e.g. for plants through urban gardening; Li *et al.*, 2009). With increasing air temperatures especially in winter time and the warming effect of urban areas, the number of established alien plants in urban areas might increase (see also 4.2.4.6.). With increasing numbers of alien species, also the BVOC (Biogenic Volatile Organic Compounds) emissions from gardened alien plants will increase (Lloyd and Fastie, 2003; see also 4.2.4.6.).

4.3.4. Impacts on Key Services

Ecosystem services are the benefits which people derive from ecosystems [see glossary]. The classification system proposed by the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2003) is widely used. It recognises *provisioning services* such as food, fiber and water (also known as 'goods' in the economic literature, and which have their own chapters in this assessment); *regulating services* such as climate regulation, pollination, pest and disease control and flood control; *supporting services* (habitat services in TEEB) which are used by people indirectly, through other services, and include items such as primary production and nutrient cycling; and *cultural services* which include recreation, aesthetic and spiritual benefits. The list of ecosystem services is long and growing; and almost all are potentially vulnerable to climate change. The provisioning services are comprehensively dealt with in chapter 3 and chapter 7, and the tourism-based services in chapter 13. This chapter focusses on those regulating services where the link to climate change has been examined.

4.3.4.1. Habitat for Biodiversity

Climate change can alter habitat for species by inducing i) shifts in habitat distribution that are not followed by species, ii) shifts in species distributions that move them outside of their preferred habitats and iii) changes in habitat quality (Urban *et al.*, 2012; Dullinger *et al.*, 2012). There is some evidence that these climate change impacts have already occurred. For example, loss of sea ice is altering habitats for polar bears and may partially explain declines in polar bear populations in some area (see also Chapter 28). However, this is not yet a widespread phenomenon. Models of future shifts in biome, vegetation type and species distributions, on the other hand, suggest that many species could be outside of their preferred habitats with the next few decades due to climate change (Urban *et al.*, 2012).

Hole *et al.* (2009) report that the majority of African birds are projected to move large distances over the next 60 years resulting in substantial turnover of species within protected areas (>50% turnover in more than 40% of Important Bird Areas of Africa) and migration across unfavorable habitats. Many birds may find suitable climate in the large network of protected areas, but will be forced to cope with new habitat constraints. Similarly, Araujo *et al.*, 2011) indicate that approximately 60% of plants and vertebrate species would no longer have favorable climates within European protected areas, often pushing them into unsuitable or less preferred habitats. Wiens *et al.* (2011) project similar effects in the western US, but also find that climate change may open up new opportunities for protecting species in areas where climate is currently unsuitable. Indeed, in some changes climate change may allow some species to move into areas of lower current or future land use pressure including protected areas (Bomhard *et al.*, 2005). These and other studies strongly argue for a rethinking of protected areas networks and of the importance of the habitat matrix outside of protected areas as a key to migration and long-term survival of species.

Over sufficiently long periods, biomes or habitat types may shift their distributions or disappear entirely due to climate change. Non-analog climates are projected to occur in the future (Williams *et al.*, 2007b; Wiens *et al.*, 2011), and in the past climate shifts have resulted in vegetation types that have no current analog (section 4.2.2). The impacts of this on species abundance and extinction risk is difficult to evaluate because species may show substantial capacity to adapt to novel habitats (Prugh *et al.*, 2008; Willis and Bhagwat, 2009; Oliver *et al.*, 2009). This high uncertainty in habitat specificity for many species means it is not possible to predict if species extinctions due to climate induced loss of habitat will be below or far above current extinction rates caused by non-climate factors (Malcolm *et al.*, 2006). This does, however, also reinforce the idea that habitat quality across all components of landscapes will increase in importance for biodiversity conservation in the future.

Effects of climate change on habitat quality are less well studied than shifts in species or habitat distributions. However, several recent studies indicate that climate change may have and probably will alter habitat quality (Iverson *et al.*, 2011; Matthews *et al.*, 2011). For example, climate change induced changes in habitat quality due to decreasing snowfall may partially explain declining songbird populations in southwestern US (Martin and Maron, 2012).

4.3.4.2. Pollination, Pest and Disease Regulation

It can be inferred that global change will result in new communities (Schweiger *et al.*, 2010). As these will have experienced a much shorter (or even no) period of coevolution, drastic changes of ecological interactions like shifts in the use of certain plants by herbivores, in the range of prey of predators or in pollination networks are to be expected (Tylianakis *et al.*, 2008; Schweiger *et al.*, 2012). This might generally result in drastic changes in the provision of services (Montoya and Raffaelli, 2010).

Among the regulating services most strongly related to biodiversity, pollination and biocontrol of pests have to be highlighted. Climate change tends to increase the abundance of pest species particularly in previously cooler climates, but assessments of changes in impacts are hard to make (Payette, 2007). Insect pests are directly influenced, e.g. through the quality of food plants (Payette and Filion, 1985) or via the effects on their natural enemies (predators and parasitoids). Direct impacts are via the relatively high temperature optima of insects, which lead to increased vitality and reproduction (Allen *et al.*, 2010a). Mild winters in temperate areas promote frost susceptible pests. For the vast majority of indirect effects, e.g. spread of insect borne diseases, information is scarce (for further assessments on climate change effects on pest and disease dynamics see WGII, chapters 7 and 11).

Climate change, after land-use changes, can be regarded as the second most relevant factor responsible for the decline of pollinators (Potts *et al.*, 2010; for other factors see Biesmeijer *et al.*, 2006; Brittain *et al.*, 2010a; Brittain *et al.*, 2010b). While the potential influence of climate change on pollination can be manifold (compare Hegland *et al.*, 2009; Roberts *et al.*, 2011; Schweiger *et al.*, 2010), there are only few observations which mostly relate to the de-coupling of plants and their pollinators – especially in relation to phenology (Gordo and Sanz, 2005). While Peñuelas and Boada (2003) states that these phenological effects may be less than feared, an analysis of phonological observations in plants Wolkovich *et al.* (2012) shows that experimental data on phenology may grossly underestimate phenological shifts. As Willmer's (2003) view is partly based upon experimental observations, it has to be seen whether field evidence might proof something different (compare Phenology Chapter 4.3.2.1.).

In relation to honeybees Le Conte and Navajas (2008) state that the generally observed decline is a clear indication for an increasing susceptibility against global change phenomena, with pesticide application, new diseases and stress (and a combination of these) as the most relevant causes. Climate change might contribute by modifying the balance between honeybees and their environment (incl. diseases). Honeybees also have shown a large capacity to adjust to a large variety of environments and their genetic variability should allow them to also cope with climatic change , that's why the preservation of genetic variability within honeybees is regarded as a central aim to mitigate climate change impacts (Le Conte and Navajas, 2008).

4.3.4.3. Climate Regulation Services

Ecosystems moderate the local climate through a range of mechanisms, including reducing the near-ground wind velocity, cooling the air through shading and the evaporation of water and ameliorating low temperatures through releasing heat absorbed during the day or summer. This service is widely recognized and valued, for instance in the establishment of windbreaks, gardens and urban parks. The focus of this section is on processes operating at much larger scales – the region to the whole globe. Terrestrial ecosystems affect climate at large scales through their influence on the physical properties of the land surface and on the composition of the atmosphere with respect to radiatively-active gases and particles. In the decade 2000-2010, approximately one fourth of the CO_2 emitted to the atmosphere by human activities was taken up by terrestrial ecosystems, reducing the rate of climate change proportionately (4.3.2.3, WG 1 Chapter 6).

One study (Arora and Montenegro, 2011) suggests that the overall effect of tropical afforestation on global temperature is up to 75% greater than would be expected on the basis of increased carbon storage alone, due to physical processes such as changes in evapotranspiration; but in other circumstances the cooling due to land-cover change may be *less* than that estimated from carbon uptake alone, due to decreased albedo (4.2.4.1). Observations and model evidence indicates that, broadly speaking, forests make warm areas cooler and cold areas warmer, through the competing effects of evapotranspiration (cooling) and surface albedo (in dark-canopied forests, generally warming). Model simulations suggest that if more than 40% of the pre-1700 extent of the Amazon forest were to be cleared, rainfall in the region would be reduced (Sampaio *et al.*, 2007). According to satellite observations, the effect of conversion of the Brazilian savannas (*cerrado*) to pasture is to induce a local warming, (Loarie *et al.*, 2011), which is partly offset when the pasture is converted to sugarcane. It has been suggested (Ridgwell *et al.*, 2009) that planting large areas of crop varieties with high-albedo leaves could help regional cooling. Model analysis indicates this strategy could be marginally effective at high latitudes, but have undesirable climate consequences at low latitudes, and measurements show that the current range of leaf albedo in major crops is insufficient to make a meaningful difference (Doughty *et al.*, 2011).

4.3.4.4. Potable Water Supply

Freshwater systems provide a range of ecosystem services that benefit society and are *likely* to be affected by climate change (see Table 4-1; Palmer and Filoso, 2009). Many of the implications of climate change on the provisioning services of water for food production and domestic supply are discussed in detail in WGII Chapter 3. Over 80% of the world's population is currently exposed to high levels of threat to water security because of land use change, pollution and water resource use (Vörösmarty *et al.*, 2010). Under climate change, reliability of surface water supply is *likely* to decrease due to increased temporal variations of river flow that are caused by increased variability in precipitation and decreased snow/ice storage (see WGII Chapter 3). In some Mediterranean regions, e.g. the southwest of Western Australia, significant reductions in surface flows have already forced governments to pursue alternative water sources (desalination, recycled wastewater) (see http://www.watercorporation.com.au/watersupply/index.html). In snow dominated regions, warming will mean that less winter precipitation falls as snow and melting of winter snow occurs earlier in spring (*high confidence*; Barnett *et al.*, 2005). This means a shift in peak discharge to winter and early spring and away from summer and autumn when human demand is highest. In some locations, water storages may not be sufficient to capture winter runoff, particularly if they are also used to safeguard downstream communities from flooding (Barnett *et al.*, 2005). Climate change not only poses risks to the quantity of water available for human society but also the quality. Warming will exacerbate many of the symptoms of eutrophication, including the increased frequency and intensity of harmful cyanobacterial blooms (Paerl and Paul, 2012). Reduced summer flows in rivers increases residence time for algal growth, increases the risk of low dissolved oxygen events and associated poor water quality, and limits the ability to dilute pollution from point sources (Jeppesen *et al.*, 2010).

4.4. Adaptation and its Limits

Wild organisms and ecosystems can adapt to climate change to some degree using intrinsic mechanisms such as migration, change in behavior and evolution: this is known as autonomous adaptation. These mechanisms rely on the availability of suitable habitat and a clear pathway to it; climate change that is sufficiently gradual to allow response by all organisms; and the retention of genetic variability. There are also biological limits to the magnitude of change which can be adapted to; for instance the tolerable body temperature of all warm-blooded animals falls within a narrow range (Clarke and Rothery, 2008). Where autonomous adaptation mechanisms are inadequate, human-assisted adaption is indicated as a supplementary approach.

4.4.1. Autonomous Adaptation by Ecosystems and Wild Organisms

Autonomous adaptation (see glossary) refers to the adjustments made by ecosystems, including their human components, without external intervention, in response to a changing environment (Smit *et al.*, 2000); also called 'spontaneous adaptation' (Smit *et al.*, 2007). In the context of human systems it is sometimes referred to as 'coping capacity'. The capacity for autonomous adaptation is necessary for resilience but is not synonymous with that term as it is now used (Walker *et al.*, 2004). Here we focus on adaptation to a changing climate in all its manifestations, recognizing that climate change in the narrow sense is necessarily associated with changing CO_2 and ozone, and in practice is usually accompanied by changing land use, abundance of competing or mutualistic organisms and other environmental stressors, such as pollution.

All systems have some capacity for autonomous adaptation, or they would not exist at all. Ecosystems which have persisted for a long time can reasonably be inferred to have a high capacity for autonomous adaptation, at least with respect to the variability which they have experienced in the past. Adaptability to one set of challenges does not automatically confer greater adaptive capacity to a different set of challenges, especially if those challenges are novel (i.e. outside the range of experience of the system). Furthermore, an environmental change that is more rapid than in the past or is accompanied by other stresses may exceed the previously-demonstrated adaptive capacity of the system. Adaptation at one level, for instance by organisms in a community, can confer greater resilience at higher organization levels, such as the ecosystem (Morecroft *et al.*, 2012). The mechanisms of autonomous adaptation of organisms and ecosystems consist of changes in the physiology, behavior, phenology or physical form of organisms, within the range permitted by their genes and the variety of genes in the population; changes in the genetic composition of the populations; and change in the composition of the community, either through in- or out-migration, or local extinction.

4.4.1.1. Phenological and Physiological

The ability to project future impacts of climate change on ecosystems is complicated by the potential for adaptations by species, which may alter apparent relationships between climate variables and species / ecosystem viability. Adaptation by individual species may increase their ability to survive and flourish under different climatic conditions, possibly leading to lower risks of extinction than predicted from statistical correlations between current distribution and climate (Botkin *et al.*, 2007), but may also affect their interdependence with other species leading to disruption of community interactions (Visser and Both, 2005).

Phenology is typically highly adapted to the climate seasonality of the environment in which the organism evolved. The phenology of any species also needs to be keyed to the phenology of other species with which it interacts, such as competitors, food species and pollinators. Thus change in phenology is a sensitive indicator of adaptation (Menzel *et al.*, 2006), but also a potential mechanism of ecosystem disruption if adaptation is insufficiently rapid or coordinated between interdependent species, or is cued to environmental signals that are not affected by climate change, such as day-length (Bradley *et al.*, 1999; Both and Visser, 2001; Parmesan, 2006). The environmental cues for phenological events are complex and multi-layered (Körner and Basler, 2010; Singer and Parmesan, 2010). For instance, late-succession temperate trees require a chilling period in winter, followed by a threshold in daylength, and only then are sensitive to temperature. As a result, projecting current phenological trends forward is risky, since the relative importance of cues can change (Cook *et al.*, 2012). The effects are complex and sometimes apparently counterintuitive, such as the increased sensitivity of flowering in high-altitude perennial herbs in the Rocky mountains to frost as a result of earlier snowmelt (Inouye, 2008).

The importance of adaptation and potential for disruption from different rates of phenological change are illustrated by the consequences of timing of migratory bird activities (see 4.3.2.1.). Breeding is most effective when synchronized with the availability of food, so changes in the phenology of food supplies can exert a selective pressure on birds. In a study of 100 European migratory bird species, those that advanced their arrival showed stable or increasing populations, while that did not adjust their arrival date on average showed declining populations (Møller *et al.*, 2008). In a comparison of nine Dutch populations of the migratory pied flycatcher (*Ficedula hypoleuca*) over two decades, populations declined by 90% in areas where food peaked early in the season and the arrival of the birds was mis-timed, unlike areas with a later food peak which can still be exploited by early-breeding birds (Both *et al.*, 2006). Selection for earlier laying dates has been shown to stronger in warmer years when food supply (caterpillars) peaked early (Coppack and Both, 2002). Systematic cross-taxa studies in the USA and UK indicate different rates of phenological change for different species and trophic levels (Parmesan, 2007; Cook *et al.*, 2008; Thackeray *et al.*, 2010).

It has been suggested that shorter generation times would give greater opportunity for autonomous adaptation through natural selection (Rosenheim and Tabashnik, 1991; Bertaux *et al.*, 2004), but a standardized assessment of 25,532 rates of phenological change for 726 UK taxa indicated that generation time only had limited influence (Thackeray *et al.*, 2010).

The physiological processes in organisms can either adapt through plasticity or genetically (i.e., through evolution). The former is generally regarded as rapid but limited, and the latter as less constrained, but slow (see 4.4.1.2) although long-term studies of a few organisms indicate rapid genetic adaptation to a changing climate (Bradshaw and Holzapfel, 2006). Acclimation to higher temperatures and/or higher CO_2 concentrations is seen in many organisms, but to very widely varying extents and general understanding remains limited (Hofmann and Todgham, 2010). A physiological process with large potential consequences for the global carbon cycle and thus the climate system is the sensitivity of the relationship between organism temperature and respiration rate, particularly in decomposer organisms (Jones *et al.*, 2003). The shape of the relationship varies between locations with different climates and shows apparent acclimation within months or years to a changing climate (Giardina and Ryan, 2000; Luo *et al.*, 2001; Rustad, 2001). The relationship is also dependent on C substrate type and the presence of other respiration-controlling environmental factors, complicating the determination of the inherent rate and its adaptation to a changing climate. Several competing hypotheses can explain the observed reduction in respiration rates in soil warming experiments after an initial peak – physiological adaptation; depletion of readily available substrate (Kirschbaum, 2004); and varying temperature sensitivities in different soil carbon pools (Knorr *et al.*, 2005).

4.4.1.2. Evolutionary and Genetic

Since the AR4 report there has been substantial progress in defining the concepts and tools necessary for documenting and predicting evolutionary and genetic responses to recent and future climate change, often referred to as "rapid evolution". Evolution can occur through many mechanisms including selection of existing resistant genes or genotypes within populations, hybridization, mutation and selection of new adaptive genes and perhaps even through epigenetics (Chevin *et al.*, 2010; Chown *et al.*, 2010; (Lavergne *et al.*, 2010; Paun *et al.*, 2010; Hoffmann and Sgro, 2011; Anderson *et al.*, 2012b; Donnelly *et al.*, 2012; Franks and Hoffmann, 2012; Hegarty, 2012; Merilä, 2012; Bell, 2013; Zhang *et al.*, 2013). Mechanisms such as selection of existing genes and genotypes, hybridization and epigenetics can lead to adaptation in very few generations, while others, notably mutation and selection of new genes, typically take at least many tens of generations. This means that species with very fast life cycles, e.g., bacteria, should in general have greater capacity to respond to climate change than species with long life cycles such as large mammals and trees. Unfortunately, there remains a paucity of observational or experimental data that can be used for detection and attribution of climate signals and for validation of models and theory.

Observed Evolutionary and Genetic Responses to Rapid Changes in Climate - There is a small, but growing body of observational evidence supporting studies reviewed in the AR4 report that some species have adapted to recent climate warming or to climatic extremes through genetic responses (e.g., plants - Franks and Weis, 2008; Anderson *et al.*, 2012a; Hill *et al.*, 2011; vertebrates - Ozgul *et al.*, 2010; Husby *et al.*, 2011; Phillimore *et al.* (2010; Karell *et al.*, 2011; insects - Buckley *et al.*, 2012; van Asch *et al.*, 2012). For example, Karell *et al.* (2011) found increasing numbers of brown genotypes of the tawny owl in Finland over the course of the last 28 years and attributed it to fewer snow-rich winters, which creates strong selection pressure against the heritable white genotype. Phillimore *et al.* (2010) showed for the common frog in Britain, that population differences in earlier spawning due to increasing spring temperatures could be attributed largely to local genetic adaptation. Using a combination of models and observations Visser and colleagues have built a case for detection and attribution of genetic adaptation in an insectivorous bird (Husby *et al.*, 2011), and in a herbivorous insect that has tracked warming related changes in the budburst timing of its host tree (van Asch *et al.*, 2012). In contrast, many species appear to be maladapted to changing climates or to respond to recent warming through phenotypic plasticity, in part because factors such as limited standing genetic variation, weak heritability of adaptive traits or conflicting constraints on adaptation create low potential for rapid evolution (Knudsen *et al.*, 2011; Ketola *et al.*, 2012; Mihoub *et al.*, 2012; Merilä, 2012). Most studies of rapid evolution suffer from methodological weakness making it difficult to clearly demonstrate a genetic basis underlying observed phenotypic responses to environmental change (Gienapp *et al.*, 2008; Franks and Hoffmann, 2012; Hansen *et al.*, 2012; Merilä, 2012). When combined with recent progress on conceptual frameworks, rapid advances in quantitative genetics, genomics and phylogenetics will substantially improve the detection and attribution of genetic responses to changing climate over the next few years (Davis *et al.*, 2010; Salamin *et al.*, 2010; Hoffmann and Sgro, 2011).

The ability of species to adapt to new environmental conditions through rapid evolutionary processes can also be inferred from the degree to which environmental niches are conserved when environment is changed. There is good evidence that environmental niches are conserved for some species under some conditions (plants - Petitpierre *et al.* (2012; birds - Monahan and Tingley, 2012; review - Peterson *et al.*, 2011), but also evidence suggesting that environmental niches can evolve over time scales of several decades following invasion or changes in climate (Broennimann *et al.*, 2007; Angetter *et al.*, 2011; Konarzewski *et al.*, 2012; Leal and Gunderson, 2012; Lavergne *et al.*, 2013). The paleontological record also provides insight into past evolutionary response in the face of natural climate variation. In general, environmental niches appear to be broadly conserved through time although there is insufficient data to determine the extent to which genetic adaptation has attenuated range shifts and changes in population size (Peterson *et al.*, 2011; Willis and MacDonald, 2011). Phylogeographic reconstructions of past species distributions suggest that hybridization may have helped avoid extinctions during cycles of glaciation and could also play a key role in future adaptation (Soliani *et al.*, 2012; Hegarty, 2012). There is also new evidence that epigenetic mechanisms, such as DNA methylation, can play a role in heritable and potentially very rapid adaptation to climate (Paun *et al.*, 2010; Zhang *et al.*, 2013), but understanding of these mechanisms is too preliminary to know how important they are for adaptation to climate change.

Mechanisms Mediating Rapid Evolutionary Response to Future Climate Change - Studies of extent genetic variability across species ranges and models that couple gene flow with spatially-explicit population dynamics suggest that populations may respond to climate change in ways that are counterintuitive. In some cases, too much or too little gene flow to populations at range margins may have created fragile, maladapted populations, which is in contrast to the current wisdom that populations at the range margins may be best adapted to global warming (Bridle *et al.*, 2010; Hill *et al.*, 2011). Conversely, there is also evidence from experiments, models and observations that populations in the center of species ranges may in some cases be more sensitive to environmental change than those at range boundaries (Bell and Gonzalez, 2009). Generalization will be complicated by the interactions between local adaptation, gene flow and population dynamics (Bridle *et al.*, 2010).

Substantial progress has been made since the AR4 report in developing models that can be used to explore whether genetic adaptation will be fast enough to track climate change. Models of long-lived tree species suggest that existing genetic variation may be sufficient to significantly attenuate negative impacts of future climate change (Kuparinen *et al.*, 2010; Kremer *et al.*, 2012), which is coherent with observations and experiments (Jump *et al.*, 2006, Jump *et al.*, 2008). However, these studies also indicate that adaptive responses will lag far behind even modest rates of projected rates of climate change, in large part due to the very long generation time of trees. In a species with much shorter generation times, the great tit (*Parus major*), Gienapp *et al.* (2013) found that modeled breeding times tracked climate change, but only at low to moderate rates of change. For a species with an even faster life cycle, van Asch *et al.*, (2007, 2012) predicted that rapid evolution of the phenological response of a herbivorous insect should have allowed it to track recent warming, which it has. This suggests substantial capacity for future adaptation in this insect since current and moderate future rates of future climate change are similar. Kearney *et al.* (2009) on the other hand found that rapid evolutionary responses only modestly affected modeled range shifts in a mosquito species in response to climate change. More broadly, Walters *et al.* (2012) found that modeled extinction risk in ecotherms - species that do not internally regulate their body temperature - is substantially reduced by genetic adaptation at rates of climate change that are roughly less than 0.02°C per generation. Based on these assumptions, species with short generation times such as most insects potentially have the capacity to genetically adapt to even the most rapid rates of projected climate change (Figure 4-6), but species with longer generation times could be at risk of extinction at moderate to high rates of climate change. Recent experimental work on "evolutionary rescue" shows that long-term avoidance of extinction through genetic adaptation to hostile environments can occur under certain conditions (Bell, 2013). Generalizations coming from experiments and theoretical work are that evolutionary rescue requires large initial genetic variation and population sizes and is accompanied by substantial loss of genetic diversity, reductions in population size and range contractions over many generations before population recovery (Bell, 2013; Schiffers *et al.*, 2013). Model-based projections must, however, be viewed with considerable caution because there are many evolutionary and ecological mechanisms that can either speed up or inhibit heritable adaptation to climate change that are not accounted for in most models (Cobben *et al.*, 2012; Norberg *et al.*, 2012; Kovach-Orr and Fussmann, 2013). In some cases, accounting for evolutionary processes in models even leads to predictions of enhanced maladaptation to climate change and more rapid population declines under certain conditions (Ferriere and Legendre, 2013). Phenotypic plasticity is thought to generally improve the odds of adaptation to climate change, but the extent to which it contributes to adaptive capacity depends a great deal on the costs of plasticity in terms of fitness (Chevin *et al.*, 2010). High plasticity in the face of climate change that has low costs can greatly improve the odds of adapting to climate change; however, plasticity that has high fitness costs can have much more modest effects on the odds of adaptation.

The AR4 report concluded that "projected rates of climate change are *very likely* to exceed rates of evolutionary adaptation in many species (*high confidence*)". Work since then provides a similar, but more nuanced view of rapid evolution in the face of climate change. There are few observational studies of rapid evolution and difficulties in detection and attribution, so there is only *medium confidence* that some species have responded to recent changes in climate through genetic adaptations, and insufficient evidence to determine if this is a widespread phenomenon (thus *low confidence* across all species). The lack of adaptation in some species to recent changes in climate, broad support for niche conservatism and models showing limited adaptive capacity especially in species with long generation times, all indicate that high rates of climate change (RCP8.5) will exceed the adaptive capacities of many species (*high confidence*). On the other hand, evidence from observations and models also indicates that there is substantial capacity for genetic adaptation to attenuate phenological shifts, population declines and local extinctions in many species, especially for low rates of climate change (RCP2.6) (*high confidence*). Projected adaptation to climate change is frequently characterized by population declines and loss of genetic diversity for many generations (*medium confidence*), thereby increasing species vulnerability to other pressures and potentially impacting ecosystem functioning and services.

4.4.1.3. Migration of Species

This mode of adaptation has been extensively dealt with in section 4.3.2.5. It is anticipated that the movement of species – individually and collectively – will continue in response to shifting climate patterns. Its effectiveness as an adaptation mechanism is constrained by three factors. First, the rate of migration for many species, in many regions of the world, is slower than the rate of movement of the climate envelope (see Figure 4-6). Second, the ecosystem interactions can only remain intact if all parts of the ecosystem migrate simultaneously and at the same rate. Thirdly, the contemporary landscape and drainage systems contain many barriers to migration, in the form of habitat fragmentation, roads, human settlements and dams.

4.4.2. Human-Assisted Adaptation

Human-assisted adaptation means a deliberate, external intervention with the intent of increasing the capacity of the target organism, ecosystem or social-ecological system to survive and function at an acceptable level in the presence of climate change (see glossary) It is also known as ‘planned adaptation’ (Smit *et al.*, 2007). This chapter focuses less on the adaptation of people, human communities and infrastructure, since they are the topics of WGII chapters 8 to 17, and more on non-human organisms and ecosystems, while acknowledging the importance of the human elements within the ecosystem. “Assistance” in this context means a range of actions, from ensuring the presence of suitable habitat and dispersal pathways and the reduction or removal of other stressors, to physically moving organisms, storing them and establishing them in new places. In addition to the other approaches assessed in this section, “Ecosystem-based Adaptation” provides an option that integrates the use of biodiversity and ecosystem services into climate change adaptation strategies in ways that can optimize co-benefits for local communities and carbon management, as well as reduce the risks associated with possible maladaption (see Box CC-EA). Note that there are risks associated with all forms human-assisted adaptation (see 4.4.4), particularly in the presence of far-from-perfect predictive capabilities (Willis and Bhagwat, 2009).

4.4.2.1. Reduction of Non-Climate Stresses and Restoration of Degraded Ecosystems

The alleviation of other stresses acting on ecosystems is suggested to increase the capacity of ecosystems to survive, and adapt to, climate change, since the effects are generally either additive or compounding. Ecosystem restoration is one way of alleviating such stresses while increasing the area available for adaptation (Harris *et al.*, 2006). Building the resilience of at-risk ecosystems by identifying the full set of drivers of change and most important areas and resources for protection is the core of the adaptation strategy for the Arctic (Christie and Sommerkorn, 2012). ‘Ecosystem-based adaptation’ is the phrase increasingly used to cover a package of protective and restorative actions aimed at increasing resilience (e.g. Colls *et al.*, 2009).

4.4.2.2. The Size, Location and Layout of Protected Areas

Additions to, or reconfigurations of, the protected area estate are commonly suggested as pre-adaptations to projected climate changes (Heller and Zavaleta, 2009). This is because for most protected areas, under plausible scenarios of climate change, a significant fraction of the biota will no longer have a viable population within the present protected area footprint. It is noted that the extant geography of protected areas is far from optimal for biodiversity protection even under the current climate; that it is cheaper to acquire land proactively in the areas of projected future bioclimatic suitability than to correct the current non-optimality and then later add on areas to deal with climate change as it unfolds (Hannah *et al.*, 2007)); and that the existing protected area network will still have utility in future climates, even though it may contain different species. Hickler *et al.* (2012) analyzed the layout of protected areas in Europe and concluded that under projected 21st century change and concluded that a third to a half of them would potentially be occupied by different vegetation than they currently represent. The new area that needs to be added to the existing protected area network to ensure future representativeness is situation-specific, but some general design rules apply: orientation along climate gradients (e.g., altitudinal gradients) is more effective than orientation across them (Roux *et al.*, 2008); regional scale planning is more effective than treating each local case independently (Heller and Zavaleta, 2009); since it is the network of habitats and protected areas that confers resilience rather than any single element; and better integration of protected areas with a biodiversity-hospitable landscape outside is more effective than treating the protected areas as islands (Willis and Bhagwat, 2009).

4.4.2.3. Landscape and Watershed Management

The general principles for management adaptations in United States were summarized from a major literature review by West *et al.*, 2009. They suggest that in the context of climate change a successful management of natural resources will require cycling between ‘managing for resilience’’ and ‘‘managing for change”. This requires the anticipation of changes that can alter the impacts of grazing, fire, logging, harvesting, recreation, and so on. At the national level, the necessary changes in practice to facilitate adaptation include: (1) management at appropriate scales, and not necessarily the scales of convenience or tradition; (2) increased collaboration among agencies; (3) rational approaches for establishing priorities and applying triage; and (4) management with the expectation of ecosystem change, rather than keeping them as they have been. Barriers and opportunities were divided into four categories: (1) legislation and regulations, (2) management policies and procedures, (3) human and financial capital, and (4) information and science.

In 14,000 ha of forested watersheds in central Nova Scotia, Canada, the adaptation to climate change was assessed using the landscape disturbance model LANDIS-II, (Steenberg *et al.*, 2011). The study simulated the impact of three components of timber harvesting: the canopy-opening size of harvests, the age of harvested trees within a stand, and the species composition of harvested trees within a stand. The combination of all three adaptation treatments allowed target species and old forest to remain reasonably well represented without diminishing the timber supply. This minimized the trade-offs between management values and climate adaptation objectives.

4.4.2.4. Assisted Migration

Assisted migration has been proposed when fragmentation of habitats limits migration potential or when natural migration rates are outstripped by the pace of climate change, (Hoegh-Guldberg *et al.*, 2008; Vitt *et al.*, 2010; Chmura *et al.*, 2011; Loss *et al.*, 2011). The options for management can be summarized as: i) try to maintain or improve existing habitat so that species don't have to move, ii) maintain or improve migration corridors, including active management to improve survival along the moving margin of the distribution (Lawson *et al.*, 2012), or iii) intervene heavily by translocating species (Hoegh-Guldberg *et al.*, 2008; Loss *et al.*, 2011). There is *low agreement* in the scientific community whether it is best to increase the resilience of ecosystems to climate change, thus help to preserve existing communities, or to enhance the capacity of ecosystems to transform in the face of the overwhelming forces of species migration and modifications of ecosystem function by climate change.

There is *high agreement* among the scientific and conservation community that maintaining or improving migration corridors or ecological networks is a low-regret strategy, partly because it is also seen as useful in combatting the negative effects of habitat fragmentation on population dynamics (Hole *et al.*, 2011; Jongman *et al.*, 2011). This approach has the benefit of improving the migration potential for large numbers of species and is therefore a more ecosystemic approach than assisted migration for individual species. However, observational and modeling studies show that increases in habitat connectivity do not always improve the population dynamics of target species, may decrease species diversity, and may also facilitate the spread of invasive species (Cadotte, 2006; Brisson *et al.*, 2010; Matthiessen *et al.*, 2010).

There is *medium agreement* that the practice of assisted migration of targeted species is a useful adaptation option (Hoegh-Guldberg *et al.*, 2008; Loss *et al.*, 2011; Vitt *et al.*, 2009; Willis and Bhagwat, 2009; Hewitt *et al.*, 2011). The speed of 21st century climate change and substantial habitat fragmentation in many areas of the world mean that many species will be unable to migrate or adapt fast enough to keep pace with climate change. If this results in significant reductions in range size it will pose problems for long-term survival of the species. Some ecologists believe that careful selection of species to be moved would minimize the risk of undesirable impacts on existing communities or ecosystem function (Minteer and Collins, 2010), but others argue that the history of intentional species introductions shows that the outcomes are unpredictable and in many cases have had disastrous impacts (Ricciardi and Simberloff, 2009). The number of species that could potentially require assisted migration that could easily overwhelm funding capacity (Minteer and Collins, 2010).The degree and magnitude of phenotypic responses or genetic adaptation to climate change are very variable among species, making decisions regarding which species should be translocated complex and debatable.

4.4.2.5. Ex Situ Conservation

Conservation of plant and animal genetic resources outside of their natural environment, in gardens, zoos, breeding programmes, seed-banks or gene-banks has been widely advocated as an ‘insurance’ against both climate change and other sources of biodiversity loss and impoverishment (Khoury *et al.*, 2010). There are many examples of existing efforts of this type, some very large and with global scope (e.g. Millennium Seed Bank, Svalbard vault). The Dixon National Tallgrass Prairie Seed Bank is an example of prioritization of species for seed banking, both for restoration purposes and for potential assisted migration in the future (Leishman *et al.*, 2007). A genome scan approach identified four potentially adaptive loci in important grassland species *Arrhenatherum elatium.* Knowledge on adaptive loci might in the long run also help to adapt ecosystems to adverse climate change effects through assisted migration of ecotypes rather than introduction of new species (Colautti *et al.*, 2010).

Several issues remain largely unresolved (Li and Pritchard, 2009). The physiological, institutional and economic sustainability of such efforts into the indefinite future is unclear. The fraction of the intra-specific variation that needs to be preserved for future viability and how much genetic bias is introduced by founder effects and selection pressures applied during ex-situ maintenance is unknown. It remains uncertain whether it is possible to reintroduce species (especially animals) successfully into the wild after generations of ex-situ conservation.

4.4.3. Consequences and Costs of Inaction and Benefits of Action

Failure to act to assist ecosystem adaptation to climate change will plausibly leads to ecological, social and economic *damages*. The necessary actions to cope with unavoidable damages generate *adaptation costs*, while *mitigation costs* are associated with actions to tackle undesired future damages. Examples of these costs, based on recent literature, are shown in Table 2-5 in Rodriguez-Labajos (submitted). The timing of the action also has cost implications: increasing costs that result from must be weighed against the risks associated with premature measures (Szlavik and Csete, 2012). In addition to the direct financial costs of action, further costs may appear through trade-offs between services: e.g. afforestation for climate mitigation is costly in terms water provision (Chisholm, 2010). Traditional agriculture preserves soil carbon sinks, supports on-site biodiversity and uses less fossil fuel than high-input agriculture (Martinez-Alier, 2011), but due to the lower per hectare yields, requires a larger area to be dedicated to cropland.

A comprehensive cost estimate of the effects of climate change on ecosystem service provision is not available. ten Brink *et al.* (2008) report the monetary cost of not meeting the 2010 biodiversity goals in terms of lost value of ecosystem services. Their model incorporates climate change, among other pressures, and concludes that cumulative losses of welfare due to losses in ecosystem service provision could reach an annual amount of 14 trillion Euro (based on values of 2007), in 2050 equivalent to 7% of projected global GDP for that year.

Economic calculations are appropriate when at least one component of the ecosystem services is traded in markets (such as for biofuels; Mishra *et al.*, 2010). If climate regulation services are translated into a tradable item, through carbon markets or payments for avoiding deforestation, then their value can be expressed via market prices (Shaw *et al.*, 2011).

The market price for carbon is volatile, linked to speculation and political agreements on emission reduction. There is a range of estimates from $23/metric ton of carbon to $371, in current 1995 and 2007 dollars respectively (Tol, 2008; Watkiss and Downing, 2008). In the South-African Fynbos region, economic viability of afforestation proved to be highly sensitive to the value of carbon (Chisholm, 2010). The realized prices of the traded carbon have been on average lower than the figures mentioned above. The proposed global REDD programs, financed by carbon-offset trading, rely on the premises on which market-based payment for ecosystem services (PES) are founded. However, a decade of PES experience demonstrates a clash between market-efficiency criteria and poverty reduction and therefore a risk of regressive wealth redistribution (McAfee, 2012).

Uncertainty about the potential consequences of abrupt changes advises against valuation of ecosystems close to critical thresholds (TEEB, 2009). Similar difficulties can be argued in the presence of irreversible changes, as in the case of irreversible biodiversity losses or damage to cultural services such as World Heritage sites (Viles and Cutler, 2012).

4.4.4. Unintended Consequences of Adaptation and Mitigation Actions in This and Other Sectors

Some issues relevant to this section are also found in 4.2.2 and in Chapter 14.

Several of the alternatives to fossil fuel require extensive use of the land surface. Bio-energy requires land to either be taken from food production or from natural ecosystems. Many renewables require significant land areas. Hydroelectricity usually involves the impoundment of large bodies of water behind dams, leading to flooding of pre-existing ecosystems. Solar energy effectively involves decreasing the albedo of areas of ground surface. Large-scale wind energy involves the location of arrays of turbines across the landscape. As an illustration, the “aggressive mitigation” scenario RPC2.6 relies heavily on both bio-energy and renewables as major components of the energy mix (van Vuuren *et al.*, 2011), so there is clear potential for unintended consequences for terrestrial and inland water systems.

In RCP2.6, although food production remains dominant, the scenario still involves some land use / land-cover change (Box 4-1) in order to facilitate the use of bio-energy. By 2100, bio-energy crops occupy approximately 4 million km^2, approximately 7% of global cultivated land projected at the time. Modification of the landscape and the fragmentation of habitats are major influences on extinction risk (Fischer and Lindenmayer, 2007), especially if native vegetation cover is reduced or degraded, human land use is intensive and “natural” areas become disconnected. Hence, additional extensification of cultivated areas for energy crops may pose extinction risks.

RCP2.6 also includes a substantial increase in renewables above current levels of deployment, either as hydropower, solar or wind. Damming of river systems for hydropower can cause fragmentation of the inland water habitat with implications for fish species, and monitoring studies indicate that flooding of ecosystems behind the dams can lead to declining populations, e.g., of amphibians (Brandão and Araújo, 2007). Large dams may also result in CH_4 emissions due to decay of flooded vegetation in anaerobic conditions and the subsequent release of CH4 from the water surface and especially from water passing through turbines and spillways (Fearnside, 2005; Lima *et al.*, 2008), so dams may act as sources of greenhouse gas emissions.

Concern is often raised over wind turbines posing a danger to birds and bats, but estimating mortality rates is complex and difficult (Smallwood, 2007). It has been estimated that wind farms in Europe and the USA cause between 0.3 and 0.4 wildlife fatalities per gigawatt-hour (GWh) of electricity, and while nuclear and fossil-fuel power stations are estimated to cause approximately 5.2 fatalities per GWh (Sovacool, 2009), although this quantification has been criticized as having key methodological flaws (Willis *et al.*, 2010b). One study found on-site bird populations to be generally affected more by windfarm construction than subsequent operation, with some populations recovering after construction (Pearce-Higgins *et al.*, 2012)

Solar energy systems, by design, aim to maximize the absorption of solar energy and hence widespread deployment of photovoltaics (PV) has the potential to exert a positive radiative forcing on climate through decreased surface albedo. In a scenario of widespread deployment of solar PV, such a forcing is estimated to be 30 times smaller than the avoided radiative forcing arising from the use of PV to substitute fossil fuels, so overall PV still exerts a net reduction of climate warming (Nemet, 2009). Nevertheless, at the local scale there are some plausible circumstances in which the decreased surface albedo substantially reduces the effectiveness of PV as a negative climate forcing (Nemet, 2009).

Adaption measures may also result in unintended consequences. Relocation of agricultural areas as a climate change adaptation measure could pose risks of habitat fragmentation and loss similar to those discussed above in the context of mitigation through bio-energy. Deliberate relocation of vulnerable and important species – assisted migration – may also be a potential conservation measure in the context of facilitating adaptation to climate change (Maclachlan *et al.*, 2007). However this may directly conflict with other conservation priorities, for example by actually facilitating the introduction of invasive species (Maclachlan *et al.*, 2007).

Proactive adaptation measures may also have unforeseen consequences politically. Carey *et al.* (2011) argue that improved water management in a glacial lake in the Peruvian Andes in 1985 led to increased tensions over many years and ultimately local civil action against the authorities in 2008. Introduction of a tunnel to reduce the risk of a glacial lake outburst flood facilitated proactive human management of the lake levels, but in the context of changes in the wider political situation, power struggles arose between different stakeholders due to different and conflicting interests. This may provide an example of how attempts by society to exert more direct control over the environment can lead to unintended impacts.

4.5. Emerging Issues and Key Uncertainties

The presence of thresholds in ecosystem response to climate change, and specifically the type of thresholds characterized as “tipping points’, is a growing concern but remains a major source of uncertainty. In general (Field *et al.*, 2007), negative feedbacks currently dominate the climate-ecosystem interaction, but in several areas, such as the boreal ecosystems, positive feedbacks could dominate, even under moderate warming. For most ecological processes, increasing magnitude of warming shifts the balance towards positive rather than negative feedbacks (Field *et al.*, 2007). For positive feedbacks to propagate into ‘runaway’ processes leading to a new ecosystem state, the strength of the feedback has to exceed that of the initial perturbation. This has not as yet been demonstrated for any large-scale, plausible and immanent ecological process; but the risk is non-negligible and the consequences if it did occur would be severe: thus further research is needed. The issue of biophysical feedbacks between ecosystem state and the climate, over and above the effects mediated through greenhouse gases, is emerging as significant in many areas. Such effects include those caused by changes in surface reflectivity (albedo) or the partitioning of energy between latent energy and sensible heat.

Uncertainty in predicting the response of ecosystems to climate and other perturbations remains a major impediment to determining prudent levels of permissible change. A significant source of this uncertainty stems from the inherent complexity of ecosystems, especially where they are coupled to equally-complex social systems. The high number of interactions can lead to cascading effects (Biggs *et al.*, 2011). Some of this uncertainty can be removed by understanding the systems better, but some will remain irreducible because of the failure of predictive models when faced with mathematical bifurcations – a problem that is well-known in climate science. Probabilistic statements about the range of outcomes are possible in this context, but ecosystem science is mostly as yet unable to conduct such analyses routinely and rigorously. One consequence is the ongoing difficulty in attributing observed changes unequivocally to climate change. More comprehensive monitoring is a key element of the solution.

Studies of the combined effects of multiple simultaneous elements of global change, such as the effects of elevated carbon dioxide and rising tropospheric ozone on plant productivity - which has critical consequences for the suture sink strength of the biosphere, since they of similar magnitude but opposite sign – are needed as a supplement to the single-factor experiments.

Understanding of the tolerable *rate* of climate change is as important as understanding the tolerable *magnitude.* Despite being explicitly required under Article 2 of the UNFCCC, rate studies are currently less developed and more uncertain than magnitude (equilibrium) studies. This includes evidence for the achievable migration rates of a range of species as well as the rate of micro-evolutionary change.

The costs of assisted adaptation ecosystems, biodiversity and ecosystem services to a changing climates is poorly known, as are the costs of failing to do so.

Frequently Asked Questions

FAQ 4.1: How does climate change contribute to species extinction?

Species extinctions are of considerable concern because they represent irreplaceable losses of unique life forms and because species loss has been shown to degrade the functioning of ecosystems in some cases. Most species extinctions in the recent past can be attributed to habitat destruction, invasive species, overexploitation and pollution. Climate change may have already contributed to the extinction of a small number of species, such as frogs and toads in Central America, but the role of climate change in these current extinctions is the subject of considerable debate. Over the coming century, climate change is foreseen to increase extinction risk because some species will not be able to adapt to new environments, nor move areas where climate becomes suitable. There is consensus that minimizing climate change will help protect species from extinctions. Under the highest rates of projected climate change, observations and models indicate that many species will be unable to move fast enough to track suitable climate or their ranges will shrink considerably. There is concern that this will substantially increase extinction risk for a large fraction of species, especially when combined with other global change pressures such as habitat destruction. We are, however, currently unable to accurately quantify this risk. Under the lowest projected rates and amounts of climate change and with the assistance of effective conservation actions, the large majority of species are foreseen to be able to adapt to the new climates, or respond by moving to higher latitudes or altitudes.

FAQ 4.2: Why does it matter that ecosystems are altered by climate change?

Ecosystems are the machinery that delivers things essential for all people, everywhere in the world – including obvious items like food, clean water and timber, but also less-obvious ones such as control of pests and diseases, regulation of the climate and a life-supporting atmosphere and pollination of flowers. When ecosystems change, their capacity to supply these services changes as well, for better or worse. Humans are directly affected, as are the millions of other species dependent on ecosystems. ”Ecosystem change” includes the species it contains and in what amounts and proportions, how the ecosystem looks (e.g. tall or short, open or dense) and how it works (e.g. whether it is productive or unproductive). Climate change, among other factors, has an effect on all these aspects of ecosystems, as well as on the total area occupied by particular ecosystems and its geographical location. Ecosystem change has knock-on effects on many sectors, including human health through altering where diseases are found, agriculture through grazing supply and pollinators, infrastructure through changing risks of flooding. Although in the long-term not all ecosystem changes are detrimental to all people or all species, rapidly-changing ecosystems will require adaptation, perhaps in excess of their adaptive capacity, by both the people and organisms dependent on them.

FAQ 4.3: What are the non-greenhouse gas effects of rising carbon dioxide?

Some greenhouse gases exert influences on the environment other than their impact on radiative forcing. The concentration of carbon dioxide affects photosynthesis and transpiration in plants, with photosynthesis generally being enhanced under higher CO_2 concentrations while transpiration is generally decreased. The growth of plants and/or the efficiency with which they use water can therefore be increased. The response varies considerably between species. Increased atmospheric CO_2 concentration also increases the acidity of water, with negative consequences for organisms with calcium carbonate shells, which cannot be grown under low pH.

FAQ 4.4: What costs are caused by changes in ecosystem services due to climate change?

Climate change will certainly alter the services provided by in ecosystems, and on balance, for high degrees of change, in an overall negative way. For instance, coral reefs protect the coast against extreme storm events, which are predicted to increase under climate change – but the reefs are at risk due to bleaching induced by temperature rise, as well as due to ocean acidification. This service alone has been valued at several 1000 $/ha per hour. Other costly damages could include a decrease in pollination services due to climate change related asynchrony of flowering time of plants and activity periods of pollinators. This service is worth worth EUR 153 billion per year (a value that nearly doubles if you take into account purchasing power parity of the affected countries)

FAQ 4.5: What are the opportunities for better managing ecosystems under climate change?

Management of ecosystems can help to mitigate climate change . Forests, for example deliver a wide set of services, including climate regulation. Ecosystems can also be managed to increase their ability to cope with climate change. Reducing the many other stresses on ecosystems – such as excessive harvest, habitat fragmentation and pollution is an important strategy. Maintaining biological diversity and near-natural disturbance regimes also helps. We may need to take drastic action such as assisting species to migrate, or protecting them out of the wild until such time as they can be reintroduced.

FAQ 4.6: Can land-use and land-cover changes cause changes in climate?

Land-use change can affect the local climate, and even the global climate. It does so by changing the emission or uptake of greenhouse gases, but also by changing how much solar energy is absorbed by the land surface. Depending on the type of change and where it occurs, the effects can be either warming or cooling. The effects on precipitation are equally variable and context-dependent. At a global scale, the conversion of forests to croplands, pastures and urban areas is currently contributing around a fifth of the overall emissions of the greenhouse gases which are causing climate change.

FAQ 4.7: Will the number of alien species increase due to climate change?

An alien species, also called exotic or non-native species is one that has been introduced to a region outside of its native geographic range as a deliberate or accidental consequence of human activity. They are called invasive when they cause ecological and/or economic damages as well as if they spread fast and produced a high amount of fertile offspring. The number of new species and the abundance of some already established alien species will increase in certain areas, such as polar regions, due to climate change improving conditions for these species, e.g. higher winter temperatures or longer growing seasons. Increased globalization of goods and human transportation and increased global land use changes are both likely to increase the frequency, establishment and damages of alien invasive species throughout the world although management actions to prevent the transfer of alien species (e.g. through treatment of ballast water and wood products and strict quarantine protocols applied to crop and horticultural products and embargos on trade and deliberate introductions of known invaders) are more and more applied. Some invasive plants and insects have already been shown to benefit from climate change and will likely establish and spread into new regions, once they are introduced there. However, other invasive species will suffer from climate change and, as for most of the biodiversity, are expected to decrease in range and population size in some regions. Within just the Family of ants, some highly invasive species are expected to benefit from climate change and increase their potential invasive areas, while some others will likely much recede.

Generally, increased establishment success and spread will be most visible for those alien species that have characteristics favored by the changing climate, such as those that are drought tolerant or able to take advantage of higher temperatures.

Cross-Chapter Boxes

Box CC-EA. Ecosystem Based Approaches to Adaptation - Emerging Opportunities

[Rebecca Shaw (USA), Jonathan Overpeck (USA), Guy Midgley (South Africa)]

Ecosystem-based approaches to adaptation (also termed Ecosystem-based Adaptation, EBA) integrate the use of biodiversity and ecosystem services into climate change adaptation strategies (e.g., CBD, 2009; Munroe *et al.*, 2011; Munroe *et al.*, 2011). EBA is implemented through the sustainable management of natural resources, as well as conservation and restoration of ecosystems, to provide and sustain services that facilitate adaptation both to climate variability and change (Colls *et al.*, 2009). The CBD COP 10 Decision X/33 on Climate Change and Biodiversity states further that effective EBA also “takes into account the multiple social, economic and cultural co-benefits for local communities”.

The potential for EBA is increasingly being realized (e.g., Munroe *et al.*, 2011), offering opportunities that integrate with or even substitute for the use of engineered infrastructure or other technological approaches. Engineered defenses such as dams, sea walls and levees, may adversely affect biodiversity, resulting in maladaptation due to damage to ecosystem regulating services (Campbell *et al.*, 2009, Munroe *et al.*, 2011). There is some evidence that the restoration and use of ecosystem services may reduce or delay the need for these engineering solutions (CBD, 2009). Well-integrated EBA is also more cost effective and sustainable than non-integrated physical engineering approaches, and may contribute to achieving sustainable development goals (e.g., poverty reduction, sustainable environmental management, and even mitigation objectives), especially when they are integrated with sound ecosystem management approaches. EBA also offers lower risk of maladaptation than engineering solutions in that their application is more flexible and responsive to unanticipated environmental changes.

EBA provides opportunities particularly in developing countries where economies depend more directly on the provision of ecosystem services (Vignola *et al.*, 2009), to reduce risks to climate change impacts and ensure that development proceeds on a pathways that are resilient to climate change (Munang *et al.*,). In these settings, ecosystem-based adaptation projects may be readily developed by enhancing existing initiatives, such as community-based adaptation and natural resource management approaches (e.g., Khan *et al.*, 2012, Midgley *et al.*, 2012; Roberts *et al.*, 2012)

Examples of ecosystem based approaches to adaptation include:

- Sustainable water management, where river basins, aquifers, flood plains, and their associated vegetation are managed or restored to provide resilient water storage and enhanced baseflows, flood regulation services, reduction of erosion/siltation rates, and more ecosystem goods (e.g., Midgley *et al.*, 2012, Opperman *et al.*, 2009).
- Disaster risk reduction through the restoration of coastal habitats (e.g., mangroves, wetlands and deltas) to provide effective measure against storm-surges, saline intrusion and coastal erosion;
- Sustainable management of grasslands and rangelands to enhance pastoral livelihoods and increase resilience to drought and flooding;
- Establishment of diverse and resilient agricultural systems, and adapting crop and livestock variety mixes to secure food provision. Traditional knowledge may contribute in this area through, for example, identifying indigenous crop and livestock genetic diversity, and water conservation techniques;
- Management of fire-prone ecosystems to achieve safer fire regimes while ensuring the maintenance of natural processes.

It is important to assess the appropriate and effective application of EBA as a developing concept through learning from work underway, and to build understanding of the social and physical conditions that may limit its effectiveness. Application of EBA, like other approaches, is not without risk, and risk/benefit assessments will allow better assessment of opportunities offered by the approach.

[INSERT FIGURE EA-1 HERE
Figure EA-1: Adapted from Munang *et al.* (2013). Ecosystem based adaptation approaches to adaptation can utilize the capacity of nature to buffer human systems from the adverse impacts of climate change through sustainable delivery of ecosystems services. A) Business as Usual Scenario in which climate impacts degrade ecosystems, ecosystem service delivery and human well-being B) Ecosystem-based Adaptation Scenario which utilizes natural capital and ecosystem services to reduce climate-related risks to human communities.]

CC-EA References

Campbell, A., Kapos, V., Scharlemann, J., Bubb, P., Chenery, A., Coad, L., Dickson, B., Doswald, N., Khan, M., Kershaw, F., and Rashid, M., 2009: *Review of the Literature on the Links between Biodiversity and Climate Change: Impacts, Adaptation and Mitigation. Technical Series No. 42.* Montreal, Canada, 124pp. pp.

CBD, 2009: *Ad Hoc Technical Expert Group: Climate Change and Biodiversity.* Montreal, Canada,pp.

Colls, A., Ash, N., and Ikkala, N., 2009: *Ecosystem-based Adaptation: a natural response to climate change.* Gland, Switzerland, 16pp pp.

Khan, A.S., Ramachandran, A., Usha, N., Punitha, S., and Selvam, V., 2012: Predicted impact of the sea-level rise at Vellar-Coleroon estuarine region of Tamil Nadu coast in India: Mainstreaming adaptation as a coastal zone management option. *Ocean & Coastal Management*, **69**, 327-339.

Midgley, G.S.M., Barnett, M., and Wågsæther, K., 2012: *Biodiversity, climate change and sustainable development – Harnessing synergies and celebrating successes. Final Technical Report.* pp.

Munang, R., Thiaw, I., Alverson, K., Mumba, M., Liu, J., and Rivington, M., 2013: Climate change and Ecosystem-based Adaptation: a new pragmatic approach to buffering climate change impacts. *Current Opinion in Environmental Sustainability*.
Munroe, R., Doswald, N., Roe, D., Reid, H., Giuliani, A., Castelli, I., and Moller, I., 2011: *Does EbA work? A review of the evidence on the effectiveness of ecosystem-based approaches to adaptation.* Nairobi, Kenya,pp.
Opperman, J.J., Galloway, G.E., Fargione, J., Mount, J.F., Richter, B.D., and Secchi, S., 2009: Sustainable floodplains through large-scale reconnection to rivers. *Science*, **326(5959)**, 1487-1488.
Roberts, D., Boon, R., Diederichs, N., Douwes, E., Govender, N., McInnes, A., McLean, C., O'Donoghue, S., and Spires, M., 2012: Exploring ecosystem-based adaptation in Durban, South Africa: "learning-by-doing" at the local government coal face. *Environment and Urbanization*, **24(1)**, 167-195.
Vignola, R., Locatelli, B., Martinez, C., and Imbach, P., 2009: Ecosystem-based adaptation to climate change: what role for policymakers, society and scientists? *Mitigation and Adaptation Strategies for Global Change*, **14(8)**, 691-696.

Box CC-RF. Impact of Climate-Change on Freshwater Ecosystems due to Altered River Flow Regimes

[Petra Döll (Germany), Stuart E. Bunn (Australia)]

It is widely acknowledged that the flow regime is a primary determinant of the structure and function of rivers and their associated floodplain wetlands, and flow alteration is considered to be a serious and continuing threat to freshwater ecosystems (Bunn and Arthington, 2002; Poff and Zimmerman, 2010; Poff *et al.*, 2010). Most species distribution models do not consider the effect of changing flow regimes (i.e. changes to the frequency, magnitude, duration and/or timing of key flow parameters) or they use precipitation as proxy for river flow (Heino *et al.*, 2009).

There is growing evidence that climate change will significantly alter ecologically important attributes of hydrologic regimes in rivers and wetlands, and exacerbate impacts from human water use in developed river basins (Aldous *et al.*, 2011; Xenopoulos *et al.*, 2005). By the 2050s, climate change is projected to impact river flow characteristics like long-term average discharge, seasonality and statistical high flows (but not statistical low flows) more strongly than dam construction and water withdrawals have done up to the year 2000 (Figure RF-1; Döll and Zhang, 2010). For one climate scenario, 15% of the global land area may suffer, by the 2050s, from a decrease of fish species in the upstream basin of more than 10%, as compared to only 10% of the land area that has already suffered from such decreases due to water withdrawals and dams (Döll and Zhang, 2010). Climate change may exacerbate the negative impacts of dams for freshwater ecosystems but may also provide opportunities for operating dams and power stations to the benefit of riverine ecosystems. This is the case if total runoff increases and, like in Sweden, the annual hydrograph becomes more similar to variation in electricity demand, i.e. with a lower spring flood and increased run-off during winter months (Renofalt *et al.*, 2010).

[INSERT FIGURE RF-1 HERE
Figure RF-1: Impact of climate change on the ecologically relevant river flow characteristics mean annual river flow and monthly low flow Q_{90} as compared to the impact of water withdrawals and dams on natural flows, as computed by a global water model (Döll and Zhang, 2010). Impact of climate change is the percent change of flow between 1961-1990 and 2041-2070 according to the emissions scenario A2 as implemented by the global climate model HadCM3. Impact of water withdrawals and reservoirs is computed by running the model with and without water withdrawals and dams that existed in 2002.]

Because biota are often adapted to a certain level of river flow variability, the larger variability of river flows that is due to increased climate variability is *likely* to select for generalist or invasive species (Ficke *et al.*, 2007). The relatively stable habitats of groundwater-fed streams in snow-dominated or glacierized basins may be altered by reduced recharge by meltwater and as a result experience more variable (possibly intermittent) flows (Hannah *et al.*, 2007). A high-impact change of flow variability is a flow regime shift from intermittent to perennial or vice versa. It is projected that until the 2050s, river flow regime shifts may occur on 5-7% of the global land area, mainly in semi-arid areas (Döll and Müller Schmied, 2012; see Chapter 3, Table 3-2).

In Africa, one third of fish species and one fifth of the endemic fish species occur in eco-regions that may experience a change in discharge or runoff of more than 40% by the 2050s (Thieme *et al.*, 2010). Eco-regions containing over 80% of Africa’s freshwater fish species and several outstanding ecological and evolutionary phenomena are *likely* to experience hydrologic conditions substantially different from the present, with alterations in long-term average annual river discharge or runoff of more than 10% due to climate change and water use (Thieme *et al.*, 2010).

Due to increased winter temperatures, freshwater ecosystems in basins with significant snow storage are affected by higher river flows in winter, earlier spring peak flows and possibly reduced summer low flows (chapter 3.2.3). Strongly increased winter peak flows may lead to a decline in salmonid populations in the Pacific Northwest of the USA of 20-40% by the 2050s (depending on the climate model) due to scouring of the streambed during egg incubation, the relatively pristine high-elevation areas being affected most (Battin *et al.*, 2007). Reductions in summer low flows will increase the competition for water between ecosystems and irrigation water users (Stewart *et al.*, 2005). Ensuring environmental flows through purchasing or leasing water rights and altering reservoir release patterns will be an important adaptation strategy (Palmer *et al.*, 2009).

Observations and models suggest that global warming impacts on glacier and snow-fed streams and rivers will pass through two contrasting phases (Burkett *et al.*, 2005; Vuille *et al.*, 2008; Jacobsen *et al.*, 2012). In the first phase, when river discharge is increased due to intensified melting, the overall diversity and abundance of species may increase. However, changes in water temperature and stream-flow may have negative impacts on narrow range endemics (Jacobsen *et al.*, 2012). In the second phase, when snowfields melt early and glaciers have shrunken to the point that late-summer stream flow is reduced, broad negative impacts are foreseen, with species diversity rapidly declining once a critical threshold of roughly 50% glacial cover is crossed (Figure RF-2).

[INSERT FIGURE RF-2 HERE
Figure RF-2: Accumulated loss of regional species richness (gamma diversity) as a function of glacial cover GCC. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%. Each data point represents a river site and lines are Lowess fits. Adapted by permission from Macmillan Publishers Ltd: *Nature Climate Change*, Jacobsen *et al.*, 2012, © 2012.]

River discharge also influences the response of river temperatures to increases of air temperature. Globally averaged, air temperature increases of 2°C, 4°C and 6°C are estimated to lead to increases of annual mean river temperatures of 1.3°C, 2.6°C and 3.8°, respectively (van Vliet *et al.*, 2011). Discharge decreases of 20% and 40% are computed to result in additional increases of river water temperature of 0.3° C and 0.8°C on average (van Vliet *et al.*, 2011). Therefore, where rivers will experience drought more frequently in the future, freshwater-dependent biota will suffer not only directly by changed flow conditions but also by drought-induced river temperature increases, as well as by related decreased oxygen and increased pollutant concentrations.

CC-RF References

Aldous, A., Fitzsimons, J., Richter, B., and Bach, L., 2011: Droughts, floods and freshwater ecosystems: evaluating climate change impacts and developing adaptation strategies. *Marine and Freshwater Research,* **62(3)**, 223-231.

Battin, J., Wiley, M.W., Ruckelshaus, M.H., Palmer, R.N., Korb, E., Bartz, K.K., and Imaki, H., 2007: Projected impacts of climate change on salmon habitat restoration. *Proceedings of the National Academy of Sciences,* **104(16)**, 6720-6725.

Bunn, S.E., and Arthington, A.H., 2002: Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. *Environmental Management,* **30(4)**, 492-507.

Burkett, V.R., Wilcox, D.A., Stottlemyer, R., Barrow, W., Fagre, D., Baron, J., Price, J., Nielsen, J.L., Allen, C.D., Peterson, D.L., Ruggerone, G., and Doyle, T., 2005: Nonlinear dynamics in ecosystem response to climatic change: Case studies and policy implications. *Ecological Complexity,* **2(4)**, 357-394.

Döll, P., and Müller Schmied, H., 2012: How is the impact of climate change on river flow regimes related to the impact on mean annual runoff? A global-scale analysis. *Environmental Research Letters,* **7(1)**.

Döll, P., and Zhang, J., 2010: Impact of climate change on freshwater ecosystems: a global-scale analysis of ecologically relevant river flow alterations. *Hydrology and Earth System Sciences,* **14(5)**, 783-799.

Ficke, A.D., Myrick, C.A., and Hansen, L.J., 2007: Potential impacts of global climate change on freshwater fisheries. *Reviews in Fish Biology and Fisheries,* **17(4)**, 581-613.

Hannah, D.M., Brown, L.E., Milner, A.M., Gurnell, A.M., McGregord, G.R., Petts, G.E., Smith, B.P.G., and Snook, D.L., 2007: Integrating climate-hydrology-ecology for alpine river systems. *Aquatic Conservation-Marine and Freshwater Ecosystems,* **17(6)**, 636-656.

Heino, J., Virkkala, R., and Toivonen, H., 2009: Climate change and freshwater biodiversity: detected patterns, future trends and adaptations in northern regions. *Biological Reviews,* **84(1)**, 39-54.

Jacobsen, D., Milner, A.M., Brown, L.E., and Dangles, O., 2012: Biodiversity under threat in glacier-fed river systems. *Nature Clim. Change,* **2(5)**, 361-364.

Palmer, M.A., Lettenmaier, D.P., Poff, N.L., Postel, S.L., Richter, B., and Warner, R., 2009: Climate change and river ecosystems: protection and adaptation options. *Environmental Management,* **44**, 1053-1068.

Poff, N.L., Richter, B.D., Arthington, A.H., Bunn, S.E., Naiman, R.J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B.P., Freeman, M.C., Henriksen, J., Jacobson, R.B., Kennen, J.G., Merritt, D.M., O'Keeffe, J.H., Olden, J.D., Rogers, K., Tharme, R.E., and Warner, A., 2010: The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology,* **55(1)**, 147-170.

Poff, N.L., and Zimmerman, J.K.H., 2010: Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology,* **55**, 194–205.

Renofalt, B.M., Jansson, R., and Nilsson, C., 2010: Effects of hydropower generation and opportunities for environmental flow management in Swedish riverine ecosystems. *Freshwater Biology,* **55(1)**, 49-67.

Stewart, I.T., Cayan, D.R., and Dettinger, M.D., 2005: Changes toward earlier streamflow timing across western North America. *Journal of Climate,* **18(8)**, 1136-1155.

Thieme, M.L., Lehner, B., Abell, R., and Matthews, J., 2010: Exposure of Africa's freshwater biodiversity to a changing climate. *Conservation Letters,* **3(5)**, 324-331.

van Vliet, M.T.H., Ludwig, F., Zwolsman, J.J.G., Weedon, G.P., and Kabat, P., 2011: Global river temperatures and sensitivity to atmospheric warming and changes in river flow. *Water Resources Research,* **47(W02544)**, 1-19.

Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B.G., and Bradley, R.S., 2008: Climate change and tropical Andean glaciers: Past, present and future. *Earth-Science Reviews,* **89(3-4)**, 79-96.

Xenopoulos, M.A., Lodge, D.M., Alcamo, J., Marker, M., Schulze, K., and Van Vuuren, D.P., 2005: Scenarios of freshwater fish extinctions from climate change and water withdrawal. *Global Change Biology,* **11(10)**, 1557-1564.

Box CC-VW. Active Role of Vegetation in Altering Water Flows Under Climate Change

[Richard Betts (UK), Dieter Gerten (Germany), Petra Döll (Germany)]

Terrestrial vegetation dynamics, carbon and water cycles are closely coupled, for example by the simultaneous transpiration and CO_2 uptake through plant stomata in the process of photosynthesis, and by feedbacks of land cover and land use change on water cycling.Numerous experimental studies have demonstrated that elevated atmospheric CO_2 concentration leads to reduced opening of stomatal apertures, associated with a decrease in leaf-level transpiration (de Boer *et al.*, 2011; Reddy *et al.*, 2011). This physiological effect of CO_2 is associated with an increased intrinsic water use efficiency (iWUE) of plants, as less water is transpired per unit of carbon assimilated. Records of stable carbon isotopes in woody plants (Peñuelas *et al.*, 2011) corroborate this finding, suggesting an increase in iWUE of mature trees by 20.5% between the 1970s and 2000s. Increases since pre-industrial times have also been found for several forest sites (Andreu-Hayles *et al.*, 2011; Gagen *et al.*, 2011; Loader *et al.*, 2011; Nock *et al.*, 2011) and in a temperate semi-natural grassland (Koehler *et al.*, 2010), although in one boreal tree species iWUE ceased to increase after 1970 (Gagen *et al.*, 2011). However, the physiological CO_2 effect is accompanied by structural changes to C3 plants (including all tree species), i.e. increased biomass production, spatial encroachment and, thus, higher transpiration, as confirmed by Free Air CO_2 Enrichment (FACE) techniques (Leakey *et al.*, 2009).

There are conflicting views on whether the direct CO_2 effects on plants already have a significant influence on evapotranspiration and runoff at global scale. AR4 reported work by Gedney *et al.*, (2006) which suggested that physiological CO_2effects (lower transpiration) contributed to a supposed global increase in runoff seen in reconstructions by (Labat *et al.*, 2004). However, a more recent dataset (Dai *et al.*, 2009) showed different runoff trends in some areas. Detection of ecosystem influences on terrestrial water flows, hence, critically depends on the availability and quality of hydrometeorological observations (Haddeland *et al.*, 2011; Lorenz and Kunstmann, 2012).

A key influence on the significance of increased iWUE for large-scale transpiration is whether overall leaf area of primary vegetation has remained approximately constant (Gedney *et al.*, 2006) or has increased in some regions due to structural CO_2effects (as assumed in models by Piao *et al.*, 2007; Gerten *et al.*, 2008). While field-based results vary considerably between sites, tree ring studies suggest that tree growth did not increase globally since the 1970s in response to climate and CO_2change (Peñuelas *et al.*, 2011; Andreu-Hayles *et al.*, 2011). However, basal area measurements at over 200 plots across the tropics suggest that biomass and growth rates in intact tropical forests have increased in recent decades (Lewis *et al.*, 2009), which is also confirmed for 55 temperate forest plots, with a suspected contribution of CO_2 rise (McMahon *et al.*, 2010). The net impact of CO_2 on global-scale transpiration and runoff therefore remains poorly constrained.

Moreover, model results differ in terms of the importance of CO_2 effects for historical runoff relative to other drivers such as climate, land use change and irrigation water withdrawal. Other than Gedney *et al.*, (2006), Piao *et al.*, (2007) and Gerten *et al.*, (2008) found that CO_2 effects on global runoff were small relative to effects of precipitation, and that land use change (which often acts to decrease evapotranspiration and to increase runoff) was of second-most importance, as also supported by Sterling *et al.*, (2012) data and model analysis. By contrast, using a shorter time period and a smaller selection of river basins, Alkama *et al.*, 2011(2011) suggested that global effects of land use change on runoff have been negligible. Oliveira *et al.*, 2011(2011) furthermore point to the importance of changes in incident solar radiation and the mediating role of vegetation; their global simulations demonstrate, for example, that a higher diffuse radiation fraction during 1960–1990 increased evapotranspiration in the tropics by 3% due to increased photosynthesis from shaded leaves. Since the anthropogenic component of the precipitation and temperature contributions(i.e. of the radiative CO_2 effect) to runoff trends is not yet established, a full attribution of anthropogenic emissions of CO_2 (and other greenhouse gases)is still missing.

Analogously, there is uncertainty about how vegetation responses to future increases in CO_2 will modulate effects of climate change on the terrestrial water balance.21st-century continental- and basin-scale runoff is projected by some models to either increase more or decrease less when CO_2-induced increases in iWUE are included in addition to climate change (Betts *et al.*, 2007; Murray *et al.*, 2012), potentially reducing an increase in water stress due to rising population or climate change (Wiltshire *et al.*, submitted) – although other models project a smaller response (Cao *et al.*, 2009). Direct effects of CO_2 on plants have been modelled to increase future global runoff by 4–5% (Gerten *et al.*, 2008) up to 13% (Nugent and Matthews, 2012), depending on the assumed CO_2 trajectory and whether feedbacks of changes in vegetation structure and distribution to the climate are accounted for. The model analysis by Alkama *et al.*, (2010) suggests that although the physiological CO_2 effect will be the second-most important factor for 21st-centuryglobal runoff and although both physiological and structural effects will amplify compared to historic conditions, runoff changes will still primarily follow the projected climatic changes. Using a large ensemble of climate change projections, Konzmann *et al.*, (2013) put hydrological changes into an agricultural perspective and suggest that direct CO_2 effects on crops reduce their irrigation requirements (Fig. CC-VW-1). Thus, adverse climate change impacts on crop yields might be partly buffered as iWUE improves (Fader *et al.*, 2010), but only if proper management abates limitation of plant growth by nutrient availability or other factors. Lower transpiration under rising CO_2 may also affect future regional climate change itself (Boucher *et al.*, 2009) and may enhance the contrast between land and ocean surface warming (Joshi *et al.*, 2008).

Application of a soil-vegetation-atmosphere-transfer model indicates complex responses of groundwater recharge to changes in different climatic variables mediated by vegetation,with computed groundwater recharge being always larger than would be expected from just accounting for changes in rainfall (McCallum *et al.*, 2010). In a warmer climate with increased atmospheric CO_2 concentration, iWUE of plants increases and leaf area may either increase or decrease, and even though precipitation may slightly decrease, groundwater recharge may increase as a net effect of these interactions (Crosbie *et al.*, 2010). Depending on the type of grass in Australia, the same change in climate is suggested to lead to either increasing or decreasing groundwater recharge in this location (Green *et al.*, 2007). For a location in the Netherlands, a biomass decrease was computed for each of eight climate scenarios indicating drier summers and wetter winters (A2 emissions scenario), using a fully coupled vegetation and variably saturated hydrological model. The resulting increase in groundwater recharge up-slope was simulated to lead to higher water tables and an extended habitat for down-slope moisture-adapted vegetation (Brolsma *et al.*, 2010).

Future anthropogenic and climate-driven land cover and land use changes will also affect regional evapotranspiration, surface and subsurface water flows, with the direction and magnitude of these changes depending on the direction and intensity of the changes in vegetation coverage,as shown e.g. for a river basin in Iowa (Schilling *et al.*, 2008) or for the Elbe river basin (Conradt *et al.*, 2012).Removal of vegetation acting as source of atmospheric moisture can change regional water cycling and decrease potential crop yields by up to 17%in regions otherwise receiving this moisture in the form of precipitation (Bagley *et al.*, 2012).Changes in vegetation coverage and structure due to long-term climate change or shorter-term extreme events such as droughts (Anderegg *et al.*, 2013) also affect the partitioning of precipitation into evapotranspiration and runoff, sometimes involving complex feedbacks with the climate system such as in the Amazon region (Port *et al.*, 2012; Saatchi *et al.*, 2013). As water, carbon and vegetation dynamics evolve synchronously and interactively under climate change (Heyder *et al.*, 2011) in that e.g. vegetation structure and composition can dynamically adapt to changing climatic and hydrologic conditions (Gerten *et al.*, 2007), it remains a challenge to disentangle the effects of future land cover changes on the water cycle.

[INSERT FIGURE VW-1 HERE
Figure VW-1: Percentage change (ensemble median across 19 GCMs used to force a vegetation and hydrology model) in net irrigation requirements of 12 major crops by the 2080s, assuming current extent of irrigation areas and current management practices. Top: impacts of climate change only; bottom: additionally considering physiological and structural crop responses to increased atmospheric CO_2 concentration. Taken from Konzmann *et al.* (2013).]

CC-VW References

Alkama, R., Decharme, B., Douville, H., and Ribes, A., 2011: Trends in Global and Basin-Scale Runoff over the Late Twentieth Century: Methodological Issues and Sources of Uncertainty. *Journal of Climate,* **24(12)**, 3000-3014.

Alkama, R., Kageyama, M., and Ramstein, G., 2010: Relative contributions of climate change, stomatal closure, and leaf area index changes to 20th and 21st century runoff change: A modelling approach using the Organizing Carbon and Hydrology in Dynamic Ecosystems (ORCHIDEE) land surface model. *Journal of Geophysical Research: Atmospheres,* **115(D17)**, n/a-n/a.

Anderegg, W.R.L., Kane, J.M., and Anderegg, L.D.L., 2013: Consequences of widespread tree mortality triggered by drought and temperature stress. *Nature Climate Change,* **3(1)**, 30-36.

Andreu-Hayles, L., Planells, O., GutiÉRrez, E., Muntan, E., Helle, G., Anchukaitis, K.J., and Schleser, G.H., 2011: Long tree-ring chronologies reveal 20th century increases in water-use efficiency but no enhancement of tree growth at five Iberian pine forests. *Global Change Biology,* **17(6)**, 2095-2112.

Bagley, J.E., Desai, A.R., Dirmeyer, P.A., and Foley, J.A., 2012: Effects of land cover change on moisture availability and potential crop yield in the world's breadbaskets. *Environmental Research Letters,* **7(1)**, 014009.

Betts, R.A., Boucher, O., Collins, M., Cox, P.M., Falloon, P.D., Gedney, N., Hemming, D.L., Huntingford, C., Jones, C.D., Sexton, D.M.H., and Webb, M.J., 2007: Projected increase in continental runoff due to plant responses to increasing carbon dioxide. *Nature,* **448(7157)**, 1037-1041.

Boucher, O., Jones, A., and Betts, R.A., 2009: Climate response to the physiological impact of carbon dioxide on plants in the Met Office Unified Model HadCM3. *Climate Dynamics,* **32(2-3)**, 237-249.

Brolsma, R.J., van Vliet, M.T.H., and Bierkens, M.F.P., 2010: Climate change impact on a groundwater-influenced hillslope ecosystem. *Water Resources Research,* **46(11)**, n/a-n/a.

Cao, L., Bala, G., Caldeira, K., Nemani, R., and Ban-Weiss, G., 2009: Climate response to physiological forcing of carbon dioxide simulated by the coupled Community Atmosphere Model (CAM3.1) and Community Land Model (CLM3.0). *Geophysical Research Letters,* **36(10)**, n/a-n/a.

Conradt, T., Koch, H., Hattermann, F., and Wechsung, F., 2012: Spatially differentiated management-revised discharge scenarios for an integrated analysis of multi-realisation climate and land use scenarios for the Elbe River basin. *Regional Environmental Change,* **12(3)**, 633-648.

Crosbie, R., McCallum, J., Walker, G., and Chiew, F.S., 2010: Modelling climate-change impacts on groundwater recharge in the Murray-Darling Basin, Australia. *Hydrogeology Journal,* **18(7)**, 1639-1656.

Dai, A., Qian, T., Trenberth, K.E., and Milliman, J.D., 2009: Changes in Continental Freshwater Discharge from 1948 to 2004. *Journal of Climate,* **22(10)**, 2773-2792.

de Boer, H.J., Lammertsma, E.I., Wagner-Cremer, F., Dilcher, D.L., Wassen, M.J., and Dekker, S.C., 2011: Climate forcing due to optimization of maximal leaf conductance in subtropical vegetation under rising CO2. *Proceedings of the National Academy of Sciences,* **108(10)**, 4041-4046.

Fader, M., Rost, S., Müller, C., Bondeau, A., and Gerten, D., 2010: Virtual water content of temperate cereals and maize: Present and potential future patterns. *Journal of Hydrology,* **384(3–4)**, 218-231.

Gagen, M., Finsinger, W., Wagner-Cremer, F., McCarroll, D., Loader, N.J., Robertson, I., Jalkanen, R., Young, G., and Kirchhefer, A., 2011: Evidence of changing intrinsic water-use efficiency under rising atmospheric CO2 concentrations in Boreal Fennoscandia from subfossil leaves and tree ring δ13C ratios. *Global Change Biology,* **17(2)**, 1064-1072.

Gedney, N., Cox, P.M., Betts, R.A., Boucher, O., Huntingford, C., and Stott, P.A., 2006: Detection of a direct carbon dioxide effect in continental river runoff records. *Nature,* **439(7078)**, 835-838.

Gerten, D., Rost, S., von Bloh, W., and Lucht, W., 2008: Causes of change in 20th century global river discharge. *Geophysical Research Letters,* **35(20)**, n/a-n/a.

Gerten, D., Schaphoff, S., and Lucht, W., 2007: Potential future changes in water limitations of the terrestrial biosphere. *Climatic Change,* **80(3-4)**, 277-299.

Green, T.R., Bates, B.C., Charles, S.P., and Fleming, P.M., 2007: Physically Based Simulation of Potential Effects of Carbon Dioxide–Altered Climates on Groundwater Recharge All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. *Vadose Zone J.,* **6(3)**, 597-609.

Haddeland, I., Clark, D.B., Franssen, W., Ludwig, F., Voß, F., Arnell, N.W., Bertrand, N., Best, M., Folwell, S., Gerten, D., Gomes, S., Gosling, S.N., Hagemann, S., Hanasaki, N., Harding, R., Heinke, J., Kabat, P., Koirala, S., Oki, T., Polcher, J., Stacke, T., Viterbo, P., Weedon, G.P., and Yeh, P., 2011: Multimodel Estimate of the Global Terrestrial Water Balance: Setup and First Results. *Journal of Hydrometeorology,* **12(5)**, 869-884.

Heyder, U., Schaphoff, S., Gerten, D., and Lucht, W., 2011: Risk of severe climate change impact on the terrestrial biosphere. *Environmental Research Letters,* **6(3)**, 034036.

Joshi, M.M., Gregory, J.M., Webb, M.J., Sexton, D.M.H., and Johns, T.C., 2008: Mechanisms for the land/sea warming contrast exhibited by simulations of climate change. *Climate Dynamics,* **30(5)**, 455-465.

Koehler, I.H., Poulton, P.R., Auerswald, K., and Schnyder, H., 2010: Intrinsic water-use efficiency of temperate seminatural grassland has increased since 1857: an analysis of carbon isotope discrimination of herbage from the Park Grass Experiment. *Global Change Biology,* **16(5)**, 1531-1541.

Konzmann, M., Gerten, D., and Heinke, J., 2013: Climate impacts on global irrigation requirements under 19 GCMs, simulated with a vegetation and hydrology model. *Hydrological Sciences Journal,* **58(1)**, 88-105.

Labat, D., Godderis, Y., Probst, J.L., and Guyot, J.L., 2004: Evidence for global runoff increase related to climate warming. *Adv. Water Res.,* **27**, 631-642.

Leakey, A.D.B., Ainsworth, E.A., Bernacchi, C.J., Rogers, A., Long, S.P., and Ort, D.R., 2009: Elevated CO2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *Journal of Experimental Botany,* **60(10)**, 2859-2876.

Lewis, S.L., Lloyd, J., Sitch, S., Mitchard, E.T.A., and Laurance, W.F., 2009: Changing Ecology of Tropical Forests: Evidence and Drivers. *Annual Review of Ecology Evolution and Systematics,* **40**, 529-549.

Loader, N.J., Walsh, R.P.D., Robertson, I., Bidin, K., Ong, R.C., Reynolds, G., McCarroll, D., Gagen, M., and Young, G.H.F., 2011: Recent trends in the intrinsic water-use efficiency of ringless rainforest trees in Borneo. *Philosophical Transactions of the Royal Society B: Biological Sciences,* **366(1582)**, 3330-3339.

Lorenz, C., and Kunstmann, H., 2012: The Hydrological Cycle in Three State-of-the-Art Reanalyses: Intercomparison and Performance Analysis. *Journal of Hydrometeorology,* **13(5)**, 1397-1420.

McCallum, J.L., Crosbie, R.S., Walker, G.R., and Dawes, W.R., 2010: Impacts of climate change on groundwater in Australia: a sensitivity analysis of recharge. *Hydrogeology Journal,* **18(7)**, 1625-1638.

McMahon, S.M., Parker, G.G., and Miller, D.R., 2010: Evidence for a recent increase in forest growth. *Proceedings of the National Academy of Sciences,* **107(8)**, 3611-3615.

Murray, S.J., Foster, P.N., and Prentice, I.C., 2012: Future global water resources with respect to climate change and water withdrawals as estimated by a dynamic global vegetation model. *Journal of Hydrology,* **448–449(0)**, 14-29.

Nock, C.A., Baker, P.J., Wanek, W., Leis, A., Grabner, M., Bunyavejchewin, S., and Hietz, P., 2011: Long-term increases in intrinsic water-use efficiency do not lead to increased stem growth in a tropical monsoon forest in western Thailand. *Global Change Biology,* **17(2)**, 1049-1063.

Nugent, K.A., and Matthews, H.D., 2012: Drivers of Future Northern Latitude Runoff Change. *Atmosphere-Ocean,* **50(2)**, 197-206.

Oliveira, P.J.C., Davin, E.L., Levis, S., and Seneviratne, S.I., 2011: Vegetation-mediated impacts of trends in global radiation on land hydrology: a global sensitivity study. *Global Change Biology,* **17(11)**, 3453-3467.

Peñuelas, J., Canadell, J.G., and Ogaya, R., 2011: Increased water-use efficiency during the 20th century did not translate into enhanced tree growth. *Global Ecology and Biogeography,* **20(4)**, 597-608.

Piao, S., Friedlingstein, P., Ciais, P., de Noblet-Ducoudré, N., Labat, D., and Zaehle, S., 2007: Changes in climate and land use have a larger direct impact than rising CO2 on global river runoff trends. *Proceedings of the National Academy of Sciences,* **104(39)**, 15242-15247.

Port, U., Brovkin, V., and Claussen, M., 2012: The influence of vegetation dynamics on anthropogenic climate change. *Earth Syst. Dynam.,* **3(2)**, 233-243.

Reddy, A.R., Rasineni, G.K., and Raghavendra, A.S., 2011: The impact of global elevated CO2 concentration on photosynthesis and plant productivity. *Current Science,* **99**, 46-57.

Saatchi, S., Asefi-Najafabady, S., Malhi, Y., Aragão, L.E.O.C., Anderson, L.O., Myneni, R.B., and Nemani, R., 2013: Persistent effects of a severe drought on Amazonian forest canopy. *Proceedings of the National Academy of Sciences,* **110(2)**, 565-570.

Schilling, K.E., Jha, M.K., Zhang, Y.-K., Gassman, P.W., and Wolter, C.F., 2008: Impact of land use and land cover change on the water balance of a large agricultural watershed: Historical effects and future directions. *Water Resources Research,* **44(7)**, n/a-n/a.

Sterling, S.M., Ducharne, A., and Polcher, J., 2012: The impact of global land-cover change on the terrestrial water cycle. *Nature Clim. Change,* **advance online publication**.

Wiltshire, A., Betts, R., Booth, B., Dennis, E., Falloon, P., Gornall, J., and McNeall, D., submitted: The relative importance of population, climate change and CO2 plant physiological forcing in determining future global water stress. *Global Environmental Change*.

Box CC-WE. The Water-Energy-Food Nexus as Linked to Climate Change

[Douglas J. Arent (USA), Petra Döll (Germany), Ken Strzepek (UNU/USA), FerencToth (IAEA/Hungary), Blanca Elena Jimenez Cisneros (Mexico), Taikan Oki (Japan)]

Water, energy, and food are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure CC-WE-1. The depth and intensity of those linkages vary enormously between regions and production systems. Some energy technologies (biofuels, hydropower, thermal power plants), transportation fuels and modes and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops) require more water than others (Chapter 3.7.2, 7.3.2, 10.2,10.3.4, McMahon and Price, 2011, Macknick et al, 2012a, Cary and Weber 2008). In irrigated agriculture, climate, crop choice and yields determine water requirements per unit of produced crop, and in areas where water must be pumped or treated, energy must be provided (Kahn and Hajra 2009, Gertenet al. 2011). While food production and transport require large amounts of energy (Pelletier et al 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water (7.3.2, Diffenbaugh et al 2012, Skaggs et al, 2012).

[INSERT FIGURE WE-1 HERE
Figure WE-1: The water-energy-food nexus as related to climate change.]

Most energy production methods require significant amounts of water, either directly (e.g. crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (Chapter 10.2.2 and 10.3.4, and Davies et al 2013, van Vliet et al 2012). Water is also required for mining, processing, and residue disposal of fossil fuels. Water for biofuels, for example, has been reported by Gerbens-Leenes et al. 2012 who computed a scenario of water use for biofuels for transport in 2030 based on the Alternative Policy Scenario of the IEA. Under this scenario, global consumptive irrigation water use for biofuel production is projected to increase from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on freshwater resources, with potential negative impacts on freshwater ecosystems. Water for energy currently ranges from a few percent to more than 50% of freshwater withdrawals, depending on the region and future water requirements will depend on electric demand growth, the portfolio of generation technologies and water management options employed (WEC 2010, Sattler et al., 2012). Future water availability for energy production will change due to climate change (Chapter 3.5.2.2).

Water may require significant amounts of energy for lifting, transport and distribution, treatment or desalination. Non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per m^3 of water vary by about a factor of 10 between different sources, e.g. locally produced or reclaimed wastewater vs. desalinated seawater (Plappally and Lienhard 2012, Macknick et al, 2012b). Groundwater (35% of total global water withdrawals, with irrigated food production being the largest user, Döll et al. 2012) is generally more energy intensive than surface water – in some countries, 40% of total energy use is for pumping groundwater. Pumping from greater depth (following falling groundwater tables) increases energy demand significantly– electricity use (kWhr/m^3) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard 2012). A lack of water security can lead to increasing energy demand and vice versa, e.g. over-irrigation in response to electricity or water supply gaps.

Other linkages through land use and management, e.g. afforestation, can affect water as well as other ecosystem services, climate and water cycles (4.4.4, Box 25-10). Land degradation often reduces efficiency of water and energy use (e.g. resulting in higher fertilizer demand and surface runoff), and many of these interactions can compromise food security (3.7.2, 4.4.4). Only a few reports have begun to evaluate the multiple interactions among energy, food, land, and water (McCornick *et al.*, 2008, Bazilian *et al.*, 2011, Bierbaum and Matson, 2013), addressing the issues from a security standpoint and describing early integrated modeling approaches. The interaction among each of these factors is influenced by the changing climate, which in turn impacts energy demand, bioproductivity and other factors (see Figure WE-1 and Wise et al, 2009), and has implications for security of supplies of energy, food and water, adaptation and mitigation pathways, air pollution reduction as well as the implications for health and economic impacts as described throughout this Assessment Report.

CC-WE References

Bazilian, M. Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, R.S.J., Yumkella, K., ; Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy, Volume 39, Issue 12, December 2011, Pages 7896-7906*

Bierbaum, R., and P. Matson, "Energy in the Context of Sustainability", Daedalus, The Alternative Energy Future, Vol.2, 90-97, 2013.

Döll, P., Hoffmann-Dobrev, H., Portmann, F.T., Siebert, S., Eicker, A., Rodell, M., Strassberg, G., Scanlon, B. (2012): Impact of water withdrawals from groundwater and surface water on continental water storage variations. J. Geodyn. 59-60, 143-156, doi:10.1016/j.jog.2011.05.001.

Davies, E., Page, K. and Edmonds, J. A., 2013. "An Integrated Assessment of Global and Regional Water Demands for Electricity Generation to 2095." *Advances in Water Resources* 52:296–313.10.1016/j.advwatres.2012.11.020.

Diffenbaugh, N.,Hertel, T., M. Scherer & M. Verma, "Response of corn markets to climate volatility under alternative energy futures", Nature Climate Change 2, 514–518 (2012)

Gerten D., Heinke H., Hoff H., Biemans H., Fader M., Waha K. (2011): Global water availability and requirements for future food production, Journal of Hydrometeorology, doi: 10.1175/2011JHM1328.1.

Khan, S., Hanjra, M. A. 2009. Footprints of water and energy inputs in food production - Global perspectives. Food Policy, 34, 130-140.

King, C. and Webber, M. E., Water intensity of transportation, Environmental Science and Technology, 2008, 42 (21), 7866-7872.

Macknick, J.; Newmark, R.; Heath, G.; Hallett, K. C.; Meldrum, J.; Nettles-Anderson, S. (2012). Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies: A Review of Existing Literature", Environmental Research Letters. Vol. 7(4), 2012a

Macknick, J.; Sattler, S.; Averyt, K.; Clemmer, S.; Rogers, J. (2012). Water Implications of Generating Electricity: Water Use Across the United States Based on Different Electricity Pathways through 2050." Environmental Research Letters. Vol. 7(4), 2012b

McCornick P.G., Awulachew S.B. and Abebe M. (2008): Water-food-energy-environment synergies and tradeoffs: major issues and case studies. Water Policy, 10: 23-36.

Plappally, A.K., and J.H. Lienhard V; Energy requirements for water production, treatment, end use, reclamation, and disposal;*Renewable and Sustainable Energy Reviews, Volume 16, Issue 7, September 2012, Pages 4818-4848*

Pelletier, N., Audsley, E. , Brodt, S. , Garnett, T., Henriksson, P,. Kendall, A., Kramer, K.J. , Murphy, D., Nemeck, T. and M. Troell, "Energy Intensity of Agriculture and Food Systems", Annual Review of Environment and Resources,36: 223-246, 2011.

Sattler, S.; Macknick, J.; Yates, D.; Flores-Lopez, F.; Lopez, A.; Rogers, J. (2012). Linking Electricity and Water Models to Assess Electricity Choices at Water-Relevant Scales. Environmental Research Letters. Vol. 7(4), October-December 2012

Shah T. (2007): Groundwater, a global assessment of scale and significance, in: Molden (ed) Comprehensive Assessment of Water Management in Agriculture, Earthscan, Colombo, International Water Management Institute.

Skaggs, R., Janetos, TC, Hibbard, KA , Rice, JS, Climate and Energy-Water-Land System Interactions; Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment, PNNL report 21185, March 2012

van Vliet, M.T.H., , J.R., Ludwig, F., Vögele, S., Lettenmaier, D. P., and Kabat, P. , Vulnerability of US and European electricity supply to climate change. Nature Climate Change, 2, 676–681(2012).

Wise, M., Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R., Smith, S.J., Janetos, A, Edmonds, J. 2009. Implications of limiting CO2 concentrations for land use and energy. Science 324, 1183-1186.

World Energy Council; Water for Energy; 2010.

References

Aakala, T., Kuuluvainen, T., Wallenius, T., and Kauhanen, H., 2011: Tree mortality episodes in the intact Picea abies-dominated taiga in the Arkhangelsk region of northern European Russia. *Journal of Vegetation Science*, **22(2)**, 322-333.

Abatzoglou, J.T., and Kolden, C.A., 2011: Climate Change in Western US Deserts: Potential for Increased Wildfire and Invasive Annual Grasses. *Rangeland Ecology & Management*, **64(5)**, 471-478.

Adamik, P., and Kral, M., 2008: Climate- and resource-driven long-term changes in dormice populations negatively affect hole-nesting songbirds. *Journal of Zoology*, **275(3)**, 209-215.

Adamik, P., and Pietruszkova, J., 2008: Advances in spring but variable autumnal trends in timing of inland wader migration. *Acta Ornithologica*, **43(2)**, 119-128.

Adams, H.D., Luce, C.H., Breshears, D.D., Allen, C.D., Weiler, M., Hale, V.C., Smith, A.M.S., and Huxman, T.E., 2012: Ecohydrological consequences of drought- and infestation- triggered tree die-off: insights and hypotheses. *Ecohydrology*, **5(2)**, 145-159.

Adrian, R., O'Reilly, C.M., Zagarese, H., Baines, S.B., Hessen, D.O., Keller, W., Livingstone, D.M., Sommaruga, R., Straile, D., Van Donk, E., Weyhenmeyer, G.A., and Winder, M., 2009: Lakes as sentinels of climate change. *Limnology and Oceanography*, **54(6)**, 2283-2297.

Ahl, D.E., Gower, S.T., Burrows, S.N., Shabanov, N.V., Myneni, R.B., and Knyazikhin, Y., 2006: Monitoring spring canopy phenology of a deciduous broadleaf forest using MODIS. *Remote Sensing of Environment*, **104(1)**, 88-95.

Ahola, M.P., Laaksonen, T., Eeva, T., and Lehikoinen, E., 2007: Climate change can alter competitive relationships between resident and migratory birds. *Journal of Animal Ecology*, **76(6)**, 1045-1052.

Aiello-Lammens, M.E., Chu-Agor, M.L., Convertino, M., Fischer, R.A., Linkov, I., and Akcakaya, H.R., 2011: The impact of sea-level rise on Snowy Plovers in Florida: integrating geomorphological, habitat, and metapopulation models. *Global Change Biology*, **17(12)**, 3644-3654.

Ainsworth, E.A., Yendrek, C.R., Sitch, S., Collins, W.J., and Emberson, L.D., 2012: The Effects of Tropospheric Ozone on Net Primary Productivity and Implications for Climate Change. *Annual Review of Plant Biology*, **63(1)**, 637-661.

Akcakaya, H.R., Butchart, S.H.M., Mace, G.M., Stuart, S.N., and Hilton-Taylor, C., 2006: Use and misuse of the IUCN Red List Criteria in projecting climate change impacts on biodiversity. *Global Change Biology*, **12(11)**, 2037-2043.

Alahuhta, J., Heino, J., and Luoto, M., 2011: Climate change and the future distributions of aquatic macrophytes across boreal catchments. *Journal of Biogeography*, **38(2)**, 383-393.

Albert, K.R., Kongstad, J., Schmidt, I.K., Ro-Poulsen, H., Mikkelsen, T.N., Michelsen, A., van der Linden, L., and Beier, C., 2012: Temperate heath plant response to dry conditions depends on growth strategy and less on physiology. *Acta Oecologica-International Journal of Ecology*, **45**, 79-87.

Albert, K.R., Ro-Poulsen, H., Mikkelsen, T.N., Michelsen, A., Van der Linden, L., and Beier, C., 2011: Effects of elevated CO2, warming and drought episodes on plant carbon uptake in a temperate heath ecosystem are controlled by soil water status. *Plant Cell and Environment*, **34(7)**, 1207-1222.

Aldous, A., Fitzsimons, J., Richter, B., and Bach, L., 2011: Droughts, floods and freshwater ecosystems: evaluating climate change impacts and developing adaptation strategies. *Marine and Freshwater Research*, **62(3)**, 223-231.

Alencar, A., Asner, G.P., Knapp, D., and Zarin, D., 2011: Temporal variability of forest fires in eastern Amazonia. *Ecological Applications*, **21(7)**, 2397-2412.

Alencar, A., Nepstad, D.C., and Vera Diaz, M.d.C., 2006: Forest understory fire in the Brazilian Amazon in ENSO and non-ENSO Years: Area burned and committed carbon emissions. *Earth Interactions*, **10(6)**, 1-17.

Alexander, H.D., Mack, M.C., Goetz, S., Loranty, M., Beck, P.S.A., and Earl, K., 2012: Effects of successional stage and tree density on carbon accumulation patterns of post-fire Cajander larch (Larix cajanderi) forests within Far Northeastern Siberia. *Ecosphere*.

Ali, A.A., Blarquez, O., Girardin, M.P., Hely, C., Tinquaut, F., El Guellab, A., Valsecchi, V., Terrier, A., Bremond, L., Genries, A., Gauthier, S., and Bergeron, Y., 2012: Control of the multimillennial wildfire size in boreal

North America by spring climatic conditions. *Proceedings of the National Academy of Sciences of the United States of America,* **109(51)**, 20966-20970.

Alkama, R., Kageyama, M., and Ramstein, G., 2012: A sensitivity study to global desertification in cold and warm climates: results from the IPSL OAGCM model. *Climate Dynamics,* **38(7-8)**, 1629-1647.

Alkemade, R., van Oorschot, M., Miles, L., Nellemann, C., Bakkenes, M., and ten Brink, B., 2009: GLOBIO3: A Framework to Investigate Options for Reducing Global Terrestrial Biodiversity Loss. *Ecosystems,* **12(3)**, 374-390.

Allan, J.D., 2004: Landscapes and riverscapes: The influence of land use on stream ecosystems. *Annual Review of Ecology Evolution and Systematics,* **35**, 257-284.

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.H., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.H., Allard, G., Running, S.W., Semerci, A., and Cobb, N., 2010a: A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management,* **259(4)**, 660-684.

Allen, J.R.M., Hickler, T., Singarayer, J.S., Sykes, M.T., Valdes, P.J., and Huntley, B., 2010b: Last glacial vegetation of northern Eurasia. *Quaternary Science Reviews,* **29(19-20)**, 2604-2618.

Alley, R.B., Marotzke, J., Nordhaus, W.D., Overpeck, J.T., Peteet, D.M., Pielke, R.A., Pierrehumbert, R.T., Rhines, P.B., Stocker, T.F., Talley, L.D., and Wallace, J.M., 2003: Abrupt climate change. *Science,* **299(5615)**, 2005-2010.

Anchukaitis, K.J., and Evans, M.N., 2010: Tropical cloud forest climate variability and the demise of the Monteverde golden toad. *Proceedings of the National Academy of Sciences of the United States of America,* **107(11)**, 5036-5040.

Anderegg, W.R.L., Anderegg, L.D.L., Sherman, C., and Karp, D.S., 2012: Effects of Widespread Drought-Induced Aspen Mortality on Understory Plants. *Conservation Biology,* **26(6)**, 1082-1090.

Anderegg, W.R.L., Kane, J.M., and Anderegg, L.D.L., 2013a: Consequences of widespread tree mortality triggered by drought and temperature stress. *Nature Climate Change,* **3(1)**, 30-36.

Anderegg, W.R.L., Plavcová, L., Anderegg, L.D.L., Hacke, U.G., Berry, J.A., and Field, C.B., 2013b: Drought's legacy: multiyear hydraulic deterioration underlies widespread aspen forest die-off and portends increased future risk. *Global Change Biology,* n/a-n/a.

Anderson, J.T., Inouye, D.W., McKinney, A.M., Colautti, R.I., and Mitchell-Olds, T., 2012a: Phenotypic plasticity and adaptive evolution contribute to advancing flowering phenology in response to climate change. *Proceedings of the Royal Society B-Biological Sciences,* **279(1743)**, 3843-3852.

Anderson, J.T., Panetta, A.M., and Mitchell-Olds, T., 2012b: Evolutionary and Ecological Responses to Anthropogenic Climate Change. *Plant Physiology,* **160(4)**, 1728-1740.

Anderson, R.G., Canadell, J.G., Randerson, J.T., Jackson, R.B., Hungate, B.A., Baldocchi, D.D., Ban-Weiss, G.A., Bonan, G.B., Caldeira, K., Cao, L., Diffenbaugh, N.S., Gurney, K.R., Kueppers, L.M., Law, B.E., Luyssaert, S., and O'Halloran, T.L., 2011: Biophysical considerations in forestry for climate protection. *Frontiers in Ecology and the Environment,* **9(3)**, 174-182.

Andreae, M.O., Rosenfeld, D., Artaxo, P., Costa, A.A., Frank, G.P., Longo, K.M., and Silva-Dias, M.A.F., 2004: Smoking rain clouds over the Amazon. *Science,* **303**, 1337-1342.

Andreu-Hayles, L., Planells, O., GutiÉRrez, E., Muntan, E., Helle, G., Anchukaitis, K.J., and Schleser, G.H., 2011: Long tree-ring chronologies reveal 20th century increases in water-use efficiency but no enhancement of tree growth at five Iberian pine forests. *Global Change Biology,* **17(6)**, 2095-2112.

Angassa, A., and Oba, G., 2008: Effects of management and time on mechanisms of bush encroachment in southern Ethiopia. *African Journal of Ecology,* **46(2)**, 186-196.

Angeler, D.G., and Goedkoop, W., 2010: Biological responses to liming in boreal lakes: an assessment using plankton, macroinvertebrate and fish communities. *Journal of Applied Ecology,* **47(2)**, 478-486.

Angert, A.L., Crozier, L.G., Rissler, L.J., Gilman, S.E., Tewksbury, J.J., and Chunco, A.J., 2011: Do species' traits predict recent shifts at expanding range edges? *Ecology Letters,* **14(7)**, 677-689.

Angetter, L.S., Lotters, S., and Rodder, D., 2011: Climate niche shift in invasive species: the case of the brown anole. *Biological Journal of the Linnean Society,* **104(4)**, 943-954.

Anyamba, A., and Tucker, C.J., 2005: Analysis of Sahelian vegetation dynamics using NOAAAVHRR NDVI data from 1981-2003. *Journal of Arid Environments,* **63(3)**, 596-614.

Aragão, L., Malhi, Y., Barbier, N., Lima, A., Shimabukuro, Y., Anderson, L., and Saatchi, S., 2008: Interactions between rainfall, deforestation and fires during recent years in the Brazilian Amazonia. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **363(1498)**, 1779-1785.

Araujo, M.B., Alagador, D., Cabeza, M., Nogues-Bravo, D., and Thuiller, W., 2011: Climate change threatens European conservation areas. *Ecology Letters*, **14(5)**, 484-492.

Araujo, M.B., and Peterson, A.T., 2012: Uses and misuses of bioclimatic envelope modeling. *Ecology*, **93(7)**, 1527-1539.

Archibald, S., Roy, D.P., van Wilgen, B.W., and Scholes, R.J., 2009: What limits fire? An examination of drivers of burnt area in southern Africa. *Global Change Biology*, **15(3)**, 613-630.

Arenas, M., Ray, N., Currat, M., and Excoffier, L., 2012: Consequences of Range Contractions and Range Shifts on Molecular Diversity. *Molecular Biology and Evolution*, **29(1)**, 207-218.

Armenteras-Pascual, D., Retana-Alumbreros, J., Molowny-Horas, R., Roman-Cuesta, R.M., Gonzalez-Alonso, F., and Morales-Rivas, M., 2011: Characterising fire spatial pattern interactions with climate and vegetation in Colombia. *Agricultural and Forest Meteorology*, **151(3)**, 279-289.

Arneth, A., Harrison, S.P., Zaehle, S., Tsigaridis, K., Menon, S., Bartlein, P.J., Feichter, J., Korhola, A., Kulmala, M., O'Donnell, D., Schurgers, G., Sorvari, S., and Vesala, T., 2010: Terrestrial biogeochemical feedbacks in the climate system. *Nature Geoscience*, **3(8)**, 525-532.

Arora, V.K., and Montenegro, A., 2011: Small temperature benefits provided by realistic afforestation efforts. *Nature Geoscience*, **4(8)**, 514-518.

Axford, Y., Briner, J.P., Cooke, C.A., Francis, D.R., Michelutti, N., Miller, G.H., Smol, J.P., Thomas, E.K., Wilson, C.R., and Wolfe, A.P., 2009: Recent changes in a remote Arctic lake are unique within the past 200,000 years. *Proceedings of the National Academy of Sciences of the United States of America*, **106(44)**, 18443-18446.

Baccini, A., Goetz, S.J., Walker, W.S., Laporte, N.T., Sun, M., Sulla-Menashe, D., Hackler, J., Beck, P.S.A., Dubayah, R., Fiedl, M.A., Samanta, S., and Houghton, R.A., 2012: Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nature Climate Change*, **2(3)**, 182-185.

Bai, Z.G., Dent, D.L., Olsson, L., and Schaepman, M.E., 2008: Proxy global assessment of land degradation. *Soil Use and Management*, **24(3)**, 223-234.

Balch, J.K., Nepstad, D.C., Brando, P.M., Curran, L.M., Portela, O., de Carvalho, O., and Lefebvre, P., 2008: Negative fire feedback in a transitional forest of southeastern Amazonia. *Global Change Biology*, **14(10)**, 2276-2287.

Balian, E.V., Segers, H., Leveque, C., and Martens, K., 2008: The freshwater animal diversity assessment: An overview of the results. *Hydrobiologia*, **595(1)**, 627-637.

Balint, M., Domisch, S., Engelhardt, C.H.M., Haase, P., Lehrian, S., Sauer, J., Theissinger, K., Pauls, S.U., and Nowak, C., 2011: Cryptic biodiversity loss linked to global climate change. *Nature Climate Change*, **1(6)**, 313-318.

Ball, J.T., Woodrow, I.E., and Berry, J.A. (eds.), 1987: *A model predicting stomatal conductance and its to the control of photosynthesis under different environmental conditions*. Martinus Nijhoff Publishers, Netherlands, pp.

Barber, V.A., Juday, G.P., and Finney, B.P., 2000: Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. *Nature*, **405(6787)**, 668-673.

Barbet-Massin, M., Thuiller, W., and Jiguet, F., 2012: The fate of European breeding birds under climate, land-use and dispersal scenarios. *Global Change Biology*, **18(3)**, 881-890.

Barbosa, I.C.R., Koehler, I.H., Auerswald, K., Lups, P., and Hans, S., 2010: Last-century changes of alpine grassland water-use efficiency: a reconstruction through carbon isotope analysis of a time-series of Capra ibex horns. *Global Change Biology*, **16(4)**, 1171-1180.

Barbour, M., Keeler-Wolf, T., and Schoenherr, A.A., 2007: *Terrestrial vegetation of California*. University of California Presspp.

Barbraud, C., Gavrilo, M., Mizin, Y., and Weimerskirch, H., 2011: Comparison of emperor penguin declines between Pointe Geologie and Haswell Island over the past 50 years. *Antarctic Science*, **23(5)**, 461-468.

Barbraud, C., and Weimerskirch, H., 2006: Antarctic birds breed later in response to climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **103(16)**, 6248-6251.

Barlow, J., and Peres, C.A., 2008: Fire-mediated dieback and compositional cascade in an Amazonian forest. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **363(1498)**, 1787-1794.

Barnett, T.P., Adam, J.C., and Lettenmaier, D.P., 2005: Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature,* **438(7066)**, 303-309.

Barnosky, A.D., Matzke, N., Tomiya, S., Wogan, G.O.U., Swartz, B., Quental, T.B., Marshall, C., McGuire, J.L., Lindsey, E.L., Maguire, K.C., Mersey, B., and Ferrer, E.A., 2011: Has the Earth's sixth mass extinction already arrived? *Nature,* **471(7336)**, 51-57.

Bartholow, J.M., 2005: Recent water temperature trends in the lower Klamath River, California. *North American Journal of Fisheries Management,* **25(1)**, 152-162.

Battarbee, R.W., Kernan, M., and Rose, N., 2009: Threatened and stressed mountain lakes of Europe: Assessment and progress. *Aquatic Ecosystem Health & Management,* **12(2)**, 118-128.

Beaumont, L.J., Pitman, A., Perkins, S., Zimmermann, N.E., Yoccoz, N.G., and Thuiller, W., 2011: Impacts of climate change on the world's most exceptional ecoregions. *Proceedings of the National Academy of Sciences of the United States of America,* **108(6)**, 2306-2311.

Beck, H.E., McVicar, T.R., van Dijk, A.I.L., Schellenkens, J., de Jeu, R.A.M., and Bruijinzeel, L.A., 2011a: Global evaluation of four AVHRR-NDVI data sets: Intercomparison and assessment against Landsat imagery. *Remote Sensing of Environment,* **115(10)**, 2547-2563.

Beck, P.S.A., and Goetz, S.J., 2011: Satellite observations of high northern latitude vegetation productivity changes between 1982 and 2008: ecological variability and regional differences. *Environmental Research Letters,* **6(4)**.

Beck, P.S.A., Juday, G.P., Claire, A., Steve, W., Emily, S., Patricia, H., James, D.H., and Goetz, S.J., 2011b: Changes in forest productivity across Alaska are captured in satellite and tree ring records. *Ecology Letters,* **14(4)**, 373–379.

Beckage, B., Osborne, B., Gavin, D.G., Pucko, C., Siccama, T., and Perkins, T., 2008: A rapid upward shift of a forest ecotone during 40 years of warming in the Green Mountains of Vermont. *Proceedings of the National Academy of Sciences of the United States of America,* **105(11)**, 4197-4202.

Beerling, D.J., and Osborne, C.P., 2006: The origin of the savanna biome. *Global Change Biology,* **12(11)**, 2023-2031.

Beier, C., Emmett, B.A., Penuelas, J., Schmidt, I.K., Tietema, A., Estiarte, M., Gundersen, P., Llorens, L., Riis-Nielsen, T., Sowerby, A., and Gorissen, A., 2008: Carbon and nitrogen cycles in European ecosystems respond differently to global warming. *Science of the Total Environment,* **407(1)**, 692-697.

Beier, C., Schmidt, I.K., and Kristensen, H.L., 2004: Effects of climate and ecosystem disturbances on biogeochemical cycling in a semi-natural terrestrial ecosystem. *Water, Air and Soil Pollution: Focus,* **4**, 191-206.

Beilman, D.W., MacDonald, G.M., Smith, L.C., and Reimer, P.J., 2009: Carbon accumulation in peatlands of West Siberia over the last 2000 years. *Global Biogeochemical Cycles,* **23(GB1012, doi:10.1029/2007GB003112,)**.

Bell, G., 2013: Evolutionary rescue and the limits of adaptation. *Philosophical Transactions of the Royal Society B-Biological Sciences,* **368(1610)**.

Bell, G., and Gonzalez, A., 2009: Evolutionary rescue can prevent extinction following environmental change. *Ecology Letters,* **12(9)**, 942-948.

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., and Courchamp, F., 2012: Impacts of climate change on the future of biodiversity. *Ecology Letters,* **15(4)**, 365-377.

Bellassen, V., Viovy, N., Luyssaert, S., Le Maire, G., Schelhaas, M.J., and Ciais, P., 2011: Reconstruction and attribution of the carbon sink of European forests between 1950 and 2000. *Global Change Biology,* **17(11)**, 3274-3292.

Belyazid, S., Kurz, D., Braun, S., Sverdrup, H., Rihm, B., and Hettelingh, J.P., 2011: A dynamic modelling approach for estimating critical loads of nitrogen based on pliant community changes under a changing climate. *Environmental Pollution,* **159(3)**, 789-801.

Bentz, B.J., Régnière, J., Fettig, C.J., Hansen, E.M., Hayes, J.L., Hicke, J.A., Kelsey, R.G., Negrón, J.F., and Seybold, S.J., 2010: Climate Change and Bark Beetles of the Western United States and Canada: Direct and Indirect Effects. *Bioscience,* **60(8)**, 602-613.

Bergstrom, A.K., and Jansson, M., 2006: Atmospheric nitrogen deposition has caused nitrogen enrichment and eutrophication of lakes in the northern hemisphere. *Global Change Biology,* **12**, 635-643.

Berkes, F., Colding, J., and Folke, C. (eds.), 2003: *Navigating social-ecological Systems. Building Resilience for Complexity and Change*. University Press, Cambridge, pp.

Bernacchi, C.J., Leakey, A.D.B., Heady, L.E., Morgan, P.B., Dohleman, F.G., McGrath, J.M., Gillespie, K.M., Wittig, V.E., Rogers, A., Long, S.P., and Ort, D.R., 2006: Hourly and seasonal variation in photosynthesis and stomatal conductance of soybean grown at future CO(2) and ozone concentrations for 3 years under fully open-air field conditions. *Plant Cell and Environment,* **29(11)**, 2077-2090.

Bernhardt, E.L., Hollingsworth, T.N., and Chapin III, F.S., 2011: Fire severity mediates climate-driven shifts in understorey community composition of black spruce stands of interior Alaska. *Journal of Vegetation Science,* **22(1)**, 32-44.

Bertaux, D., Reale, D., McAdam, A.G., and Boutin, S., 2004: Keeping pace with fast climate change: can arctic life count on evolution? *Integrative and Comparitive Biology,* **44(2)**, 140-151.

Bertelsmeier, C., Luque, G., and Courchamp, F., 2012: Global warming may freeze the invasion of big-headed ants. *Biological Invasions*, 1-12.

Bertrand, R., Lenoir, J., Piedallu, C., Riofrio-Dillon, G., de Ruffray, P., Vidal, C., Pierrat, J.C., and Gegout, J.C., 2011: Changes in plant community composition lag behind climate warming in lowland forests. *Nature,* **479(7374)**, 517-520.

Betts, R.A., Arnell, N.W., Boorman, P., Cornell, S.E., House, J.I., Kaye, N.R., McCarthy, M.P., McNeall, D., Sanderson, M.G., and Wiltshire, A.J., 2012: Climate change impacts and adaptation: an Earth system view. Understanding the Earth System: Global Change Science for Application. . In *Understanding the Earth System: Global Change Science for Application.* [S. Cornell, C. Prentice, J. House & C. Downy (eds.)]. Cambridge University Press, Cambridge, pp. 160-201.

Betts, R.A., Golding, N., Gonzalez, P., Gornall, J., Kahana, R., Kay, G., Mitchell, L., and Wiltshire, A., submitted: Climate and land use change impacts on global terrestrial ecosystems, fire, and river flows in the HadGEM2-ES Earth System Model using the Representative Concentration Pathways.

Bhatt, U.S., Walker, D.A., Raynolds, M.K., Comiso, J.C., Epstein, H.E., Jia, G.S., Gens, R., Pinzon, J.E., Tucker, C.J., Tweedie, C.E., and Webber, P.J., 2010: Circumpolar Arctic Tundra Vegetation Change Is Linked to Sea Ice Decline. *Earth Interactions,* **14(8)**, 1-20.

Biesmeijer, J.C., Roberts, S.P.M., Reemer, M., Ohlemuller, R., Edwards, M., Peeters, T., Schaffers, A.P., Potts, S.G., Kleukers, R., Thomas, C.D., Settele, J., and Kunin, W.E., 2006: Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. *Science,* **313(5785)**, 351-354.

Biggs, D., Biggs, R., Dakos, V., Scholes, R.J., and Schoon, M., 2011: Are We Entering an Era of Concatenated Global Crises? *Ecology and Society,* **16(2)**.

Biggs, R., Carpenter, S.R., and Brock, W.A., 2009: Turning back from the brink: Detecting an impending regime shift in time to avert it. *Proceedings of the National Academy of Sciences of the United States of America,* **106(3)**, 826-831.

Birdsey, R.A., Pregitzer, K.S., and Lucier, A., 2006: Forest carbon management in the United States: 1600-2100. *Journal of Environmental Quality,* **35(4)**, 1461-1469.

Birks, H.J.B., and Willis, K.J., 2008: Alpines, trees, and refugia in Europe. *Plant Ecology & Diversity,* **1(2)**, 147-160.

Bleeker, A., Hicks, W.K., Dentener, E., Galloway, J., and Erisman, J.W., 2011: N deposition as a threat to the World's protected areas under the Convention on Biological Diversity. *Environmental Pollution,* **159(10)**, 2280-2288.

Blok, D., Heijmans, M.M.P.D., Schaepman-Strub, G., Kononov, A.V., Maximov, T.C., and Berendse, F., 2010: Shrub expansion may reduce summer permafrost thaw in Siberian tundra. *Global Change Biology,* **16(4)**, 1296-1305.

Bloor, J., Pichon, P., Falcimagne, R., Leadley, P., and Soussana, J.-F., 2010: Effects of Warming, Summer Drought, and CO<sub>2</sub> Enrichment on Aboveground Biomass Production, Flowering Phenology, and Community Structure in an Upland Grassland Ecosystem. *Ecosystems,* **13(6)**, 888-900.

BMT WBM, 2010: *Kakadu - Vulnerability to climate change impacts. A report to the Australian Government Department of Climate Change and Energy Efficiency.* 1-226 pp.

Bobbink, R., Hicks, K., Galloway, J., Spranger, T., Alkemade, R., Ashmore, M., Bustamante, M., Cinderby, S., Davidson, E., Dentener, F., Emmett, B., Erisman, J.W., Fenn, M., Gilliam, F., Nordin, A., Pardo, L., and De Vries, W., 2010: Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis. *Ecological Applications,* **20(1)**, 30-59.

Boggs, C.L., and Inouye, D.W., 2012: A single climate driver has direct and indirect effects on insect population dynamics. *Ecology Letters,* **15(5)**, 502-508.

Boisvenue, C., and Running, S.W., 2006: Impacts of climate change on natural forest productivity - evidence since the middle of the 20th century. *Global Change Biology,* **12(5)**, 862-882.

Bolte, A., Ammer, C., Lof, M., Madsen, P., Nabuurs, G.J., Schall, P., Spathelf, P., and Rock, J., 2009: Adaptive forest management in central Europe: Climate change impacts, strategies and integrative concept. *Scandinavian Journal of Forest Research,* **24(6)**, 473-482.

Bolte, A., and Degen, B., 2010: Forest adaptation to climate change - options and limitations. *Landbauforschung,* **60(3)**, 111-117.

Bolte, A., Hilbrig, L., Grundmann, B., Kampf, F., Brunet, J., and Roloff, A., 2010: Climate change impacts on stand structure and competitive interactions in a southern Swedish spruce-beech forest. *European Journal of Forest Research,* **129(3)**, 261-276.

Bomhard, B., Richardson, D.M., Donaldson, J.S., Hughes, G.O., Midgley, G.F., Raimondo, D.C., Rebelo, A.G., Rouget, M., and Thuiller, W., 2005: Potential impacts of future land use and climate change on the Red List status of the Proteaceae in the Cape Floristic Region, South Africa. *Global Change Biology,* **11(9)**, 1452-1468.

Bonan, G.B., 2008: Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests. *Science,* **320(5882)**, 1444-1449.

Bond-Lamberty, B., Peckham, S.D., Ahl, D.E., and Gower, S.T., 2007: Fire as the dominant driver of central Canadian boreal forest carbon balance. *Nature,* **450(7166)**, 89-92

Bond-Lamberty, B., and Thomson, A., 2010: Temperature-associated increases in the global soil respiration record. *Nature,* **464(7288)**, 579-582.

Bond, N.R., Lake, P.S., and Arthington, A.H., 2008: The impacts of drought on freshwater ecosystems: an Australian perspective. *Hydrobiologia,* **600(1)**, 3-16.

Bond, W.J., and Midgley, G.F., 2012: Carbon dioxide and the uneasy interactions of trees and savannah grasses. *Philos Trans R Soc Lond B Biol Sci,* **367(1588)**, 601-612.

Bond, W.J., and Midgley, J.J., 2001: Ecology of sprouting in woody plants: the persistence niche. *Trends in Ecology & Evolution,* **16(1)**, 45-51.

Bonfils, C.J.W., Phillips, T.J., Lawrence, D.M., Cameron-Smith, P., Riley, W.J., and Subin, Z.M., 2012: On the influence of shrub height and expansion on northern high latitude climate. *Environmental Research Letters,* **7(1)**.

Bontemps, J.D., Herve, J.C., Leban, J.M., and Dhote, J.F., 2011: Nitrogen footprint in a long-term observation of forest growth over the twentieth century. *Trees-Structure and Function,* **25(2)**, 237-251.

Booth, R.K., Jackson, S.T., Forman, S.L., Kutzbach, J.E., Bettis, E.A., Kreig, J., and Wright, D.K., 2005: A severe centennial-scale drought in mid-continental North America 4200 years ago and apparent global linkages. *Holocene,* **15(3)**, 321-328.

Both, C., Bouwhuis, S., Lesselis, C.M., and Visser, M.E., 2006: Climate change and population declines in a long-distance migratory bird. *Nature,* **441(7089)**, 81-83.

Both, C., Van Turnhout, C.A.M., Bijlsma, R.G., Siepel, H., Van Strien, A.J., and Foppen, R.P.B., 2010: Avian population consequences of climate change are most severe for long-distance migrants in seasonal habitats. *Proceedings of the Royal Society B-Biological Sciences,* **277(1685)**, 1259-1266.

Both, C., and Visser, M.E., 2001: Adjustment to climate change is constrained by arrival date in a long-distance migrant bird. *Nature,* **411(6835)**, 296-298.

Botkin, D.B., Saxe, H., Araujo, M.B., Betts, R., Bradshaw, R.H.W., Cedhagen, T., Chesson, P., Dawson, T.P., Etterson, J.R., Faith, D.P., Ferrier, S., Guisan, A., Hansen, A.S., Hilbert, D.W., Loehle, C., Margules, C., New, M., Sobel, M.J., and Stockwell, D.R.B., 2007: Forecasting the effects of global warming on biodiversity. *Bioscience,* **57(3)**, 227-236.

Boucher, O., Randall, D., and Others, in preparation: Clouds and Aerosols. In *The Physical Science Basis: Contribution of Working Group 1 to the 5th Assessment Report of the Intergovernmental Panel on Climate Change* [T. F. Stocker (ed.)]. pp.

Boutton, T.W., Liao, J.D., Filley, T.R., and Archer, S.R., 2009: Belowground carbon storage and dynamics accompanying woody plant encroachment in a subtropical savanna. In *Soil Carbon Sequestration and the Greenhouse Effect.* Madision, WI, pp. 181-205.

Bowman, D., Balch, J.K., Artaxo, P., Bond, W.J., Carlson, J.M., Cochrane, M.A., D'Antonio, C.M., DeFries, R.S., Doyle, J.C., Harrison, S.P., Johnston, F.H., Keeley, J.E., Krawchuk, M.A., Kull, C.A., Marston, J.B., Moritz, M.A., Prentice, I.C., Roos, C.I., Scott, A.C., Swetnam, T.W., van der Werf, G.R., and Pyne, S.J., 2009: Fire in the Earth System. *Science,* **324(5926)**, 481-484.

Bowman, D.M.J.S., Murphy, B.P., and Banfai, D.S., 2011: Has global environmental change caused monsoon rainforests to expand in the Australian monsoon tropics? *Landscape Ecology,* **25(8)**, 1247-1260.

Bradley, B.A., Blumenthal, D.M., Wilcove, D.S., and Ziska, L.H., 2010: Predicting plant invasions in an era of global change. *Trends in Ecology & Evolution,* **25(5)**, 310-318.

Bradley, B.A., Oppenheimer, M., and Wilcove, D.S., 2009: Climate change and plant invasions: restoration opportunities ahead? *Global Change Biology,* **15(6)**, 1511-1521.

Bradley, N.L., Leopold, A.C., Ross, J., and Huffnaker, W., 1999: Phenological changes reflect climate change in Wisconsin. *Proceedings of the National Academy of Sciences of the United States of America,* **96(17)**, 9701-9704.

Bradshaw, W.E., and Holzapfel, C.M., 2006: Evolutionary response to rapid climate change. *Science,* **312(5779)**, 1477-1478.

Brandão, R.A., and Araújo, A.F.B., 2007: Changes in Anuran Species Richness and Abundance Resulting from Hydroelectric Dam Flooding in Central Brazil. *Biotropica,* **40(2)**, 263-266.

Brando, P.M., Goetz, S.J., Baccini, A., Nepstad, D.C., Beck, P.S.A., and Christman, M.C., 2010: Seasonal and interannual variability of climate and vegetation indices across the Amazon. *Proceedings of the National Academy of Sciences of the United States of America,* **107(33)**, 14685-14690.

Brando, P.M., Nepstad, D.C., Balch, J.K., Bolker, B., Christman, M.C., Coe, M.T., and Putz, F.E., 2012: Fire-induced tree mortality in a neotropical forest: the roles of bark traits, tree size, wood density and fire behavior. *Global Change Biology,* **18(2)**, 630-641.

Brasier, C., and Webber, J., 2010: Plant pathology: Sudden larch death. *Nature,* **466(7308)**, 824-825.

Breshears, D.D., 2006: The grassland-forest continuum: trends in ecosystem properties for woody plant mosaics? *Frontiers in Ecology and the Environment,* **4(2)**, 96-104.

Breshears, D.D., Cobb, N.S., Rich, P.M., Price, K.P., Allen, C.D., Balice, R.G., Romme, W.H., Kastens, J.H., Floyd, M.L., Belnap, J., Anderson, J.J., Myers, O.B., and Meyer, C.W., 2005: Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Sciences of the United States of America,* **102(42)**, 15144-15148.

Bridle, J.R., Polechova, J., Kawata, M., and Butlin, R.K., 2010: Why is adaptation prevented at ecological margins? New insights from individual-based simulations. *Ecology Letters,* **13(4)**, 485-494.

Briffa, K.R., Shishov, V.V., Melvin, T.M., Vaganov, E.A., Grudd, H., Hantemirov, R.M., Eronen, M., and Naurzbaev, M.M., 2008: Trends in recent temperature and radial tree growth spanning 2000 years across northwest Eurasia. *Philosophical Transactions of the Royal Society B-Biological Sciences,* **363(1501)**, 2271-2284.

Brink, V.C., 1959: A Directional Change in the Subalpine Forest-Heath Ecotone in Garibaldi Park, British Columbia. *Ecology,* **40(1)**, 10-16.

Brisson, J., de Blois, S., and Lavoie, C., 2010: Roadside as Invasion Pathway for Common Reed (Phragmites australis). *Invasive Plant Science and Management,* **3(4)**, 506-514.

Brittain, C., Bommarco, R., Vighi, M., Barmaz, S., Settele, J., and Potts, S.G., 2010a: The impact of an insecticide on insect flower visitation and pollination in an agricultural landscape. *Agricultural and Forest Entomology,* **12(3)**, 259-266.

Brittain, C.A., Vighi, M., Bommarco, R., Settele, J., and Potts, S.G., 2010b: Impacts of a pesticide on pollinator species richness at different spatial scales. *Basic and Applied Ecology,* **11(2)**, 106-115.

Britton, A.J., Beale, C.M., Towers, W., and Hewison, R.L., 2009: Biodiversity gains and losses: Evidence for homogenisation of Scottish alpine vegetation. *Biological Conservation,* **142(8)**, 1728-1739.

Britton, J.R., Cucherousset, J., Davies, G.D., Godard, M.J., and Copp, G.H., 2010: Non-native fishes and climate change: predicting species responses to warming temperatures in a temperate region. *Freshwater Biology,* **55(5)**, 1130-1141.

Broadmeadow, M.S.J., Ray, D., and Samuel, C.J.A., 2005: Climate change and the future for broadleaved tree species in Britain. *Forestry,* **78(2)**, 145-161.

Broennimann, O., Treier, U.A., Muller-Scharer, H., Thuiller, W., Peterson, A.T., and Guisan, A., 2007: Evidence of climatic niche shift during biological invasion. *Ecology Letters,* **10(8)**, 701-709.

Brommer, J.E., Lehikoinen, A., and Valkama, J., 2012: The Breeding Ranges of Central European and Arctic Bird Species Move Poleward. *PLoS One,* **7(9)**.

Bronson, D.R., Gower, S.T., Tanner, M., and Van Herk, I., 2009: Effect of ecosystem warming on boreal black spruce bud burst and shoot growth. *Global Change Biology,* **15(6)**, 1534-1543.

Brook, B.W., 2008: Synergies between climate change, extinctions and invasive vertebrates. *Wildlife Research,* **35(3)**, 249-252.

Brook, B.W., and Bowman, D.M.J.S., 2006: Postcards from the past: charting the landscape-scale conversion of tropical Australian savanna to closed forest during the 20th century. *Landscape Ecology,* **21(8)**, 1253-1266.

Brook, B.W., Sodhi, N.S., and Bradshaw, C.J.A., 2008: Synergies among extinction drivers under global change. *Trends in Ecology & Evolution,* **23(8)**, 453-460.

Brouwers, N., Matusick, G., Ruthrof, K., Lyons, T., and Hardy, G., 2013: Landscape-scale assessment of tree crown dieback following extreme drought and heat in a Mediterranean eucalypt forest ecosystem. *Landscape Ecology,* **28(1)**, 69-80.

Brouwers, N.C., Mercer, J., Lyons, T., Poot, P., Veneklaas, E., and Hardy, G., 2012: Climate and landscape drivers of tree decline in a Mediterranean ecoregion. *Ecology and Evolution,* **3(1)**, 67-79.

Brown, C.D., 2010: *Tree-line Dynamics: Adding Fire to Climate Change Prediction* pp.

Brown, L.E., Hannah, D.M., and Milner, A.M., 2007: Vulnerability of alpine stream biodiversity to shrinking glaciers and snowpacks. *Global Change Biology,* **13(5)**, 958-966.

Bryant, M.D., 2009: Global climate change and potential effects on Pacific salmonids in freshwater ecosystems of southeast Alaska. *Climatic Change,* **95(1-2)**, 169-193.

Buckley, J., Butlin, R.K., and Bridle, J.R., 2012: Evidence for evolutionary change associated with the recent range expansion of the British butterfly, Aricia agestis, in response to climate change. *Molecular Ecology,* **21(2)**, 267-280.

Buisson, L., and Grenouillet, G., 2009: Contrasted impacts of climate change on stream fish assemblages along an environmental gradient. *Diversity and Distributions,* **15(4)**, 613-626.

Buisson, L., Thuiller, W., Lek, S., Lim, P., and Grenouillet, G., 2008: Climate change hastens the turnover of stream fish assemblages. *Global Change Biology,* **14(10)**, 2232-2248.

Buitenwerf, R., Bond, W.J., Stevens, N., and Trollope, W.W., 2012: Increased tree densities in two South African savannas: > 50 years of data suggests CO2 as a driver. . *Global Change Biology,* **18(2)**, 675-684.

Bunn, S.E., and Arthington, A.H., 2002: Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. *Environmental Management,* **30(4)**, 492-507.

Burgmer, T., Hillebrand, H., and Pfenninger, M., 2007: Effects of climate-driven temperature changes on the diversity of freshwater macroinvertebrates. *Oecologia,* **151(1)**, 93-103.

Burkhead, N.M., 2012: Extinction Rates in North American Freshwater Fishes, 1900-2010. *Bioscience,* **62(9)**, 798-808.

Burrows, M.T., Schoeman, D.S., Buckley, L.B., Moore, P., Poloczanska, E.S., Brander, K.M., Brown, C., Bruno, J.F., Duarte, C.M., Halpern, B.S., Holding, J., Kappel, C.V., Kiessling, W., O'Connor, M.I., Pandolfi, J.M., Parmesan, C., Schwing, F.B., Sydeman, W.J., and Richardson, A.J., 2011: The Pace of Shifting Climate in Marine and Terrestrial Ecosystems. *Science,* **334(6056)**, 652-655.

Burton, O.J., Phillips, B.L., and Travis, J.M.J., 2010: Trade-offs and the evolution of life-histories during range expansion. *Ecology Letters,* **13(10)**, 1210-1220.

Buswell, J.M., Moles, A.T., and Hartley, S., 2011: Is rapid evolution common in introduced plant species? *Journal of Ecology,* **99(1)**, 214-224.

Butt, N., de Oliveira, P.A., and Costa, M.H., 2011: Evidence that deforestation affects the onset of the rainy season in Rondonia, Brazil. *Journal of Geophysical Research-Atmospheres,* **116(D11120)**, 1-8.

Cabral, A.C., Miguel, J.M., Rescia, A.J., Schmitz, M.F., and Pineda, F.D., 2009: Shrub encroachment in Argentinean savannas. *Journal of Vegetation Science,* **14(2)**, 145-152.

Cadotte, M.W., 2006: Dispersal and species diversity: A meta-analysis. *American Naturalist,* **167(6)**, 913-924.

Caesar, J., Palin, E., Liddicoat, S., Lowe, J., Burke, E., Pardaens, A., Sanderson, M., and Kahana, R., 2012: Response of the HadGEM2 Earth System Model to future greenhouse gas emissions pathways. *Journal of Climate*.

Cahill, A.E., Aiello-Lammens, M.E., Fisher-Reid, M.C., Hua, X., Karanewsky, C.J., Ryu, H.Y., Sbeglia, G.C., Spagnolo, F., Waldron, J.B., Warsi, O., and Wiens, J.J., 2013: How does climate change cause extinction? *Proceedings of the Royal Society B-Biological Sciences,* **280(1750)**.

Cailleret, M., Nourtier, M., Amm, A., Durand-Gillmann, M., and Davi, H., 2013: Drought-induced decline and mortality of silver fir differ among three sites in Southern France. *Annals of Forest Science,* 1-15.

Caissie, D., 2006: The thermal regime of rivers: a review. *Freshwater Biology,* **51(8)**, 1389-1406.

Caldow, R.W.G., Stillman, R.A., Durell, S.E.A.l.V.d., West, A.D., McGrorty, S., Goss-Custard, J.D., Wood, P.J., and Humphreys, J., 2007: Benefits to shorebirds from invasion of a non-native shellfish. *Proceedings of the Royal Society B-Biological Sciences,* **274(1616)**, 1449-1455.

Cameron, A., 2012: Refining risk estimates using models. In *Saving a Million Species: Extinction Risk from Climate Change* [L. Hannah (ed.)]. Island Press, Washington, Covelo, London, pp. 41-72.

Canadell, J.G., Le Quéré, C., Raupach, M.R., Field, C.B., Buitenhuis, E.T., Ciais, P., Conway, T.J., Gillett, N.P., Houghton, R.A., and Marland, G., 2007: Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the National Academy of Sciences*, **104(47)**, 18866-18870.

Cannone, N., Diolaiuti, G., Guglielmin, M., and Smiraglia, C., 2008: Accelerating climate change impacts on alpine glacier forefield ecosystems in the European Alps. *Ecological Applications*, **18(3)**, 637-648.

Cannone, N., Sgorbati, S., and Guglielmin, M., 2007: Unexpected impacts of climate change on alpine vegetation. *Frontiers in Ecology and the Environment*, **5(7)**, 360-364.

Capon, S.J., 2007: Effects of flooding on seedling emergence from the soil seed bank of a large desert floodplain. *Wetlands*, **27(4)**, 904-914.

Carey, M., French, A., and O'Brien, E., 2011: Unintended effects of technology on climate change adaptation: an historical analysis of water conflicts below Andean Glaciers. *Journal of Historical Geography*, **38(2012)**, 181-191.

Carmo, J.B.d., de Sousa Neto, E.R., Duarte-Neto, P.J., Ometto, J.P.H.B., and Martinelli, L.A., 2012: Conversion of the coastal Atlantic forest to pasture: Consequences for the nitrogen cycle and soil greenhouse gas emissions. *Agriculture, Ecosystems & Environment*, **148(0)**, 37-43.

Carney, K.M., Hungate, B.A., Drake, B.G., and Megonigal, J.P., 2007: Altered soil microbial community at elevated CO2 leads to loss of soil carbon. *Proceedings of the National Academy of Sciences of the United States of America*, **104(12)**, 4990-4995.

Carnicer, J., Coll, M., Ninyerola, M., Pons, X., Sanchez, G., and Penuelas, J., 2011: Widespread crown condition decline, food web disruption, and amplified tree mortality with increased climate change-type drought. *Proceedings of the National Academy of Sciences of the United States of America*, **108(4)**, 1474-1478.

Chapin III, F.S., Sturm, M., Serreze, M.C., McFadden, J.P., Key, J.R., Lloyd, A.H., McGuire, A.D., Rupp, T.S., Lynch, A.H., Schimel, J.P., Beringer, J., Chapman, W.L., Epstein, H.E., Euskirchen, E.S., Hinzman, L.D., Jia, G., Ping, C.L., Tape, K.D., Thompson, C.D.C., Walker, D.A., and Welker, J.M., 2005: Role of land-surface changes in Arctic summer warming. *Science*, **310(5748)**, 657-660.

Charru, M., Seynave, I., Morneau, F., and Bontemps, J.D., 2010: Recent changes in forest productivity: An analysis of national forest inventory data for common beech (Fagus sylvatica L.) in north-eastern France. *Forest Ecology and Management*, **260(5)**, 864-874.

Cheaib, A., Badeau, V., Boe, J., Chuine, I., Delire, C., Dufrêne, E., François, C., Gritti, E.S., Legay, M., Pagé, C., Thuiller, W., Viovy, N., and Leadley, P., 2012: Climate change impacts on tree ranges: model intercomparison facilitates understanding and quantification of uncertainty. *Ecology Letters*, **15(6)**, 533-544.

Chen, I.-C., Hill, J.K., Ohlemüller, R., Roy, D.B., and Thomas, C.D., 2011: Rapid Range Shifts of Species Associated with High Levels of Climate Warming. *Science*, **333(6045)**, 1024-1026.

Chen, I.C., Shiu, H.J., Benedick, S., Holloway, J.D., Cheye, V.K., Barlow, H.S., Hill, J.K., and Thomas, C.D., 2009: Elevation increases in moth assemblages over 42 years on a tropical mountain. *Proceedings of the National Academy of Sciences of the United States of America*, **106(5)**, 1479-1483.

Chessman, B.C., 2009: Climatic changes and 13-year trends in stream macroinvertebrate assemblages in New South Wales, Australia. *Global Change Biology*, **15(11)**, 2791-2802.

Chevin, L.M., Lande, R., and Mace, G.M., 2010: Adaptation, Plasticity, and Extinction in a Changing Environment: Towards a Predictive Theory. *Plos Biology*, **8(4)**.

Chiba, S., and Roy, K., 2011: Selectivity of terrestrial gastropod extinctions on an oceanic archipelago and insights into the anthropogenic extinction process. *Proceedings of the National Academy of Sciences of the United States of America*, **108(23)**, 9496-9501.

Chisholm, R.A., 2010: Trade-offs between ecosystem services: Water and carbon in a biodiversity hotspot. *Ecological Economics*, **69(10)**, 1973-1987.

Chmura, D.J., Anderson, P.D., Howe, G.T., Harrington, C.A., Halofsky, J.E., Peterson, D.L., Shaw, D.C., and St Clair, J.B., 2011: Forest responses to climate change in the northwestern United States: Ecophysiological foundations for adaptive management. *Forest Ecology and Management*, **261(7)**, 1121-1142.

Choat, B., Jansen, S., Brodribb, T.J., Cochard, H., Delzon, S., Bhaskar, R., Bucci, S.J., Feild, T.S., Gleason, S.M., Hacke, U.G., Jacobsen, A.L., Lens, F., Maherali, H., Martinez-Vilalta, J., Mayr, S., Mencuccini, M., Mitchell, P.J., Nardini, A., Pittermann, J., Pratt, R.B., Sperry, J.S., Westoby, M., Wright, I.J., and Zanne, A.E., 2012: Global convergence in the vulnerability of forests to drought. *Nature*, **491(7426)**, 752-+.

Chown, S.L., Hoffmann, A.A., Kristensen, T.N., Angilletta, M.J., Stenseth, N.C., and Pertoldi, C., 2010: Adapting to climate change: a perspective from evolutionary physiology. *Climate Research*, **43(1-2)**, 3-15.

Chown, S.L., Huiskes, A.H.L., Gremmen, N.J.M., Lee, J.E., Terauds, A., Crosbie, K., Frenot, Y., Hughes, K.A., Imura, S., Kiefer, K., Lebouvier, M., Raymond, B., Tsujimoto, M., Ware, C., van den Vijver, B., and Bergstrom, D.M., 2012: Continent-wide risk assessment for the establishment of nonindigenous species in Antarctica. *Proceedings of the National Academy of Sciences of the United States of America*, **109(13)**, 4938-4943.

Christie, P., and Sommerkorn, M., 2012: *RaCeR: Rapid assessment of Circum-arctic ecosystem Resilience* WWf Global arctic programme, Ottawa, Canada, 72-72 pp.

Chuine, I., Morin, X., Sonie, L., Collin, C., Fabreguettes, J., Degueldre, D., Salager, J.L., and Roy, J., 2012: Climate change might increase the invasion potential of the alien C4 grass Setaria parviflora (Poaceae) in the Mediterranean Basin. *Diversity and Distributions*, **18(7)**, 661-672.

Churkina, G., Zaehle, S., Hughes, J., Viovy, N., Chen, Y., Jung, M., Heumann, B.W., Ramankutty, N., Heimann, M., and Jones, C., 2010: Interactions between nitrogen deposition, land cover conversion, and climate change determine the contemporary carbon balance of Europe. *Biogeosciences*, **7(9)**, 2749-2764.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogee, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A.D., Friedlingstein, P., Grunwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T., and Valentini, R., 2005: Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature*, **437(7058)**, 529-533.

Ciais, P., Sabine, C., and others, in press: Carbon and Biogeochemical Cycles. In *Contribution of Working Group 1 to the 5th Assessment Report of the Intergovernmental Panel on Climate Change* [T. F. Stocker (ed.)]. pp.

Ciais, P., Schelhaas, M.J., Zaehle, S., Piao, L., Cescatti, A., Liski, J., Luyssaert, S., Le-Maire, G., Schulze, E.D., Bouriaud, O., Freibauer, A., Valentini, R., and Nabuurs, G.J., 2008: Carbon accumulation in European forests. *Nature Geoscience*, **1(7)**, 425-429.

Clark, D.A., Piper, S.C., Keeling, C.D., and Clark, D.B., 2003: Tropical rain forest tree growth and atmospheric carbon dynamics linked to interannual temperature variation during 1984-2000. *Proceedings of the National Academy of Sciences of the United States of America*, **100(10)**, 5852-5857.

Clark, J.S., 1998: Why trees migrate so fast: Confronting theory with dispersal biology and the paleorecord. *American Naturalist*, **152(2)**, 204-224.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., and McCabe, A.M., 2009: The Last Glacial Maximum. *Science*, **325(5941)**, 710-714.

Clarke, A., and Rothery, P., 2008: Scaling of body temperature in mammals and birds. *Functional Ecology*, **22**, 58-67.

Claussen, M., 2009: Late Quaternary vegetation-climate feedbacks. *Climate of the Past*, **5(2)**, 203-216.

Clavero, M., Villero, D., and Brotons, L., 2011: Climate change or land use dynamics: Do we know what climate change indicators indicate? *PLoS One*, **6(4)**, e18581.

Cleland, E., and Harpole, W.S., 2010: Nitrogen enrichment and plant communities. *Annals of the New York Academy of Sciences*, **1195(1)**, 46-61.

Cleland, E.E., Allen, J.M., Crimmins, T.M., Dunne, J.A., Pau, S., Travers, S., Zavaleta, E.S., and Wolkovich, E.M., 2012: Phenological tracking enables positive species responses to climate change. *Ecology*, **93(8)**, 1765–1771.

Cleland, E.E., Chuine, I., Menzel, A., Mooney, H.A., and Schwartz, M.D., 2007: Shifting plant phenology in response to global change. *Trends in Ecology & Evolution*, **22(7)**, 357-365.

Clements, D.R., and Ditommaso, A., 2011: Climate change and weed adaptation: can evolution of invasive plants lead to greater range expansion than forecasted? *Weed Research*, **51(3)**, 227-240.

Cobben, M.M.P., Verboom, J., Opdam, P.F.M., Hoekstra, R.F., Jochem, R., and Smulders, M.J.M., 2012: Wrong place, wrong time: climate change-induced range shift across fragmented habitat causes maladaptation and declined population size in a modelled bird species. *Global Change Biology*, **18(8)**, 2419-2428.

Cochrane, M.A., 2003: Fire science for rainforests. *Nature*, **421**, 913-919.

Cochrane, M.A., and Barber, C.P., 2009: Climate change, human land use and future fires in the Amazon. *Global Change Biology*, **15(3)**, 601-612.

Colautti, R.I., Eckert, C.G., and Barrett, S.C.H., 2010: Evolutionary constraints on adaptive evolution during range expansion in an invasive plant. *Proceedings of the Royal Society B-Biological Sciences*, **277(1689)**, 1799-1806.

Collatz, M.H., Ribbas-Carbo, M., and Berry, J.A., 1992: Coupled photosynthesis-stomatal conductances model for leaves of C4 plants. *Australian Journal of Plant Physiology*, **19**, 519-538.

Collins, J.P., 2010: Amphibian decline and extinction: What we know and what we need to learn. *Diseases of Aquatic Organisms*, **92(2-3)**, 93-99.

Collins, W.J., Sitch, S., and Boucher, O., 2010: How vegetation impacts affect climate metrics for ozone precursors. *Journal of Geophysical Research-Atmospheres*, **115(D23308)**, 1-14.

Colls, A., Ash, N., and Ikkala, N., 2009: *Ecosystem-based Adaptation: a natural response to climate change.* Gland, Switzerland, 16 pp.

Colwell, R.K., Brehm, G., Cardelus, C.L., Gilman, A.C., and Longino, J.T., 2008: Global warming, elevational range shifts, and lowland biotic attrition in the wet tropics. *Science*, **322(5899)**, 258-261.

Conlisk, E., Lawson, D., Syphard, A.D., Franklin, J., Flint, L., Flint, A., and Regan, H.M., 2012: The Roles of Dispersal, Fecundity, and Predation in the Population Persistence of an Oak (Quercus engelmannii) under Global Change. *Plos One*, **7(5)**.

Connell, J.H., 1978: Diversity in tropical rain forests and coral reefs. *Science*, **199**, 1302–1310.

Cook, B.I., Cook, E.R., Huth, P.C., Thompson, J.E., Forster, A., and Smiley, D., 2008: A cross-taxa phenological dataset from Mohonk Lake, NY and its relationship to climate. *International Journal of Climatology*, **28(10)**, 1369-1383.

Cook, B.I., Wolkovich, E.M., and Parmesan, C., 2012: Divergent responses to spring and winter warming drive community level flowering trends. *Proceedings of the National Academy of Sciences of the United States of America*, **(in press)**.

Cooper, O.R., Parrish, D.D., Stohl, A., Trainer, M., Nedelec, P., Thouret, V., Cammas, J.P., Oltmans, S.J., Johnson, B.J., Tarasick, D., Leblanc, T., McDermid, I.S., Jaffe, D., Gao, R., Stith, S., Ryerson, T., Aikin, K., Campos, T., Weinheimer, A., and Avery, A.M., 2010: Increasing springtime ozone mixing ratios in the free troposphere over western North America. *Nature*, **463(12)**, 344-348.

Coppack, T., and Both, C., 2002: Predicting life-cycle adaptation of migratory birds to global climate change. *Ardea*, **90(3)**, 369-378.

Corlett, R.T., 2011: Impacts of warming on tropical lowland rainforests. *Trends in Ecology & Evolution*, **26(11)**, 606-613.

Costa, M.H., Yanagi, S.N.M., Souza, P., Ribeiro, A., and Rocha, E.J.P., 2007: Climate change in Amazonia caused by soybean cropland expansion, as compared to caused by pastureland expansion. *Geophysical Research Letters*, **34(7)**.

Cox, P.M., Betts, R.A., Jones, C.D., Spall, S.A., and Totterdell, I.J., 2000: Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature*, **408(6809)**, 184-187.

Cox, P.M., Huntingford, C., and Harding, R.J., 1998: A canopy conductance and photosynthesis model for use in a GCM land surface scheme. . *Journal of Hydrology*, **212-213**, 79–94.

Cox, P.M., Pearson, D., Booth, B.B., Friedlingstein, P., Huntingford, C., Jones, C.D., and Luke, C.M., 2013: Sensitivity of tropical carbon to climate change constrained by carbon dioxide variability. *Nature*, **advance online publication**.

Crimmins, S.M., Dobrowski, S.Z., Greenberg, J.A., Abatzoglou, J.T., and Mynsberge, A.R., 2011: Changes in Climatic Water Balance Drive Downhill Shifts in Plant Species' Optimum Elevations. *Science*, **331(6015)**, 324-327.

Crimmins, T.M., Crimmins, M.A., and Bertelsen, C.D., 2009: Flowering range changes across an elevation gradient in response to warming summer temperatures. *Global Change Biology*, **15(5)**, 1141-1152.

Crous, C.J., Jacobs, S.M., and Esler, K.J., 2012: Drought-tolerance of an invasive alien tree, *Acacia mearnsii* and two native competitors in fynbos riparian ecotones. *Biological Invasions*, **14(3)**, 619-631.

Cui, X.F., and Graf, H.F., 2009: Recent land cover changes on the Tibetan Plateau: a review. *Climatic Change*, **94(1-2)**, 47-61.

Cullen, L.E., Stewart, G.H., Duncan, R.P., and Palmer, J.G., 2001: Disturbance and climate warming influences on New Zealand Nothofagus tree-line population dynamics. *Journal of Ecology*, **89(6)**, 1061-1071.

Curran, L.M., Trigg, S.N., McDonald, A.K., Astiani, D., Hardiono, Y.M., Siregar, P., Caniago, I., and Kasischke, E., 2004: Lowland forest loss in protected areas of Indonesian Borneo. *Science*, **303(5660)**, 1000-1003.

da Costa, A.C.L., Galbraith, D., Almeida, S., Portela, B.T.T., Da Costa, M., De Athaydes Silva Junior, J., Braga, A.P., De Gonçalves, P.H.L., De Oliveira, A.A., Fisher, R., Phillips, O.L., Metcalfe, D.B., Levy, P., and Meir, P., 2010: Effect of 7 yr of experimental drought on vegetation dynamics and biomass storage of an eastern Amazonian rainforest. *New Phytologist*, **187(3)**, 579-591.

Dahm, C.N., Baker, M.A., Moore, D.I., and Thibault, J.R., 2003: Coupled biogeochemical and hydrological responses of streams and rivers to drought. *Freshwater Biology*, **48(7)**, 1219-1231.

Dai, F., Su, Z., Liu, S., and Liu, G., 2011: Temporal variation of soil organic matter content and potential determinants in Tibet, China. *Catena*, **85(3)**, 288-294.

Dale, V.H., Tharp, M.L., Lannom, K.O., and Hodges, D.G., 2010: Modeling transient response of forests to climate change. *Science of the Total Environment*, **408(8)**, 1888-1901.

Danby, R.K., and Hik, D.S., 2007: Variability, contingency and rapid change in recent subarctic alpine tree line dynamics. *Journal of Ecology*, **95(2)**, 352-363.

Daniau, A.L., Bartlein, P.J., Harrison, S.P., Prentice, I.C., Brewer, S., Friedlingstein, P., Harrison-Prentice, T.I., Inoue, J., Izumi, K., Marlon, J.R., Mooney, S., Power, M.J., Stevenson, J., Tinner, W., Andric, M., Atanassova, J., Behling, H., Black, M., Blarquez, O., Brown, K.J., Carcaillet, C., Colhoun, E.A., Colombaroli, D., Davis, B.A.S., D'Costa, D., Dodson, J., Dupont, L., Eshetu, Z., Gavin, D.G., Genries, A., Haberle, S., Hallett, D.J., Hope, G., Horn, S.P., Kassa, T.G., Katamura, F., Kennedy, L.M., Kershaw, P., Krivonogov, S., Long, C., Magri, D., Marinova, E., McKenzie, G.M., Moreno, P.I., Moss, P., Neumann, F.H., Norstrom, E., Paitre, C., Rius, D., Roberts, N., Robinson, G.S., Sasaki, N., Scott, L., Takahara, H., Terwilliger, V., Thevenon, F., Turner, R., Valsecchi, V.G., Vanniere, B., Walsh, M., Williams, N., and Zhang, Y., 2012: Predictability of biomass burning in response to climate changes. *Global Biogeochemical Cycles*, **26(GB4007, doi:10.1029/2011GB004249)**.

Daniau, A.L., Harrison, S.P., and Bartlein, P.J., 2010: Fire regimes during the Last Glacial. *Quaternary Science Reviews*, **29(21-22)**, 2918-2930.

Daufresne, M., and Boet, P., 2007: Climate change impacts on structure and diversity of fish communities in rivers. *Global Change Biology*, **13(12)**, 2467-2478.

Davidson, A.M., Jennions, M., and Nicotra, A.B., 2011: Do invasive species show higher phenotypic plasticity than native species and, if so, is it adaptive? A meta-analysis. *Ecology Letters*, **14(4)**, 419-431.

Davidson, E.A., and Janssens, I.A., 2006: Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, **440**, 165-173.

Davies, T.J., Smith, G.F., Bellstedt, D.U., Boatwright, J.S., Bytebier, B., Cowling, R.M., Forest, F., Harmon, L.J., Muasya, A.M., Schrire, B.D., Steenkamp, Y., van der Bank, M., and Savolainen, V., 2011: Extinction Risk and Diversification Are Linked in a Plant Biodiversity Hotspot. *Plos Biology*, **9(5)**.

Davin, E.L., and de Noblet-Ducoudre, N., 2010: Climatic Impact of Global-Scale Deforestation: Radiative versus Nonradiative Processes. *Journal of Climate*, **23(1)**, 97-112.

Davin, E.L., de Noblet-Ducoudre, N., and Friedlingstein, P., 2007: Impact of land cover change on surface climate: Relevance of the radiative forcing concept. *Geophysical Research Letters*, **34(13)**.

Davis, C.C., Willis, C.G., Primack, R.B., and Miller-Rushing, A.J., 2010: The importance of phylogeny to the study of phenological response to global climate change. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **365(1555)**, 3201-3213.

Davis, J.L., S. , and Thompson, R., 2010: Freshwater biodiversity and climate change. In *Managing climate change: papers from the Greenhouse 2009 conference* [I. Jubb, P. Holper & W. Cai (eds.)]. CSIRO Publishing, Collingwood, Australia, pp. 73-84.

Dawes, M.A., Hättenschwiler, S., Bebi, P., Hagedorn, F., Handa, I.T., Körner, C., and Rixen, C., 2011: Species-specific tree growth responses to 9 years of CO2 enrichment at the alpine treeline. *Journal of Ecology*, **99(2)**, 383-394.

Dawson, T.P., Jackson, S.T., House, J.I., Prentice, I.C., and Mace, G.M., 2011: Beyond Predictions: Biodiversity Conservation in a Changing Climate. *Science*, **332(6025)**, 53-58.

de Jong, R., de Bruin, S., de Wit, A., Schaepman, M.E., and Dent, D.L., 2011: Analysis of monotonic greening and browning trends from global NDVI time-series. *Remote Sensing of Environment*, **115(2)**, 692-702.

De Kauwe, M.G., Medlyn, B.E., Zaehle, S., Walker, A.P., Dietze, M.C., Hickler, T., Jain, A.K., Luo, Y., Parton, W.J., Prentice, C., Smith, B., Thornton, P.E., Wang, S., Wang, Y.-P., Wårlind, D., Weng, E.S., Crous, K.Y., Ellsworth, D.S., Hanson, P.J., Seok-Kim, H., Warren, J.M., Oren, R., and Norby, R.J., 2013: Forest water use and water use efficiency at elevated CO2: a model-data intercomparison at two contrasting temperate forest FACE sites. *Global Change Biology*, in press.

de Vries, W., and Posch, M., 2011: Modelling the impact of nitrogen deposition, climate change and nutrient limitations on tree carbon sequestration in Europe for the period 1900-2050. *Environmental Pollution*, **159(10)**, 2289-2299.

DeFries, R.S., Rudel, T., Uriarte, M., and Hansen, M., 2010: Deforestation driven by urban population growth and agricultural trade in the twenty-first century. *Nature Geoscience*, **3(3)**, 178-181.

Delire, C., de Noblet-Ducoudre, N., Sima, A., and Gouirand, I., 2011: Vegetation Dynamics Enhancing Long-Term Climate Variability Confirmed by Two Models. *Journal of Climate*, **24(9)**, 2238-2257.

DeMichele, C., Accatino, F., Vezzoli, R., and Scholes, R.J., 2011: Savanna domain in the herbivores-fire parameter space exploiting a tree–grass–soil water dynamic model. *Journal of Theoretical Biology*, **289**, 74-82.

Denman, K.L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P.M., Dickinson, R.E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., da Silva Dias, P.L., Wofsy, S.C., and Zhang, X., 2007: Couplings Between Changes in the Climate System and Biogeochemistry. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., pp.

Dentener, F., Keating, T., and Akimoto, H., 2010: *Hemispheric Transport of Air Pollution part A: Ozone and Particulate Matter.* UNECE Air Pollution Series Series 17, 304 pp.

DeRose, R.J., and Long, J.N., 2012: Drought-driven disturbance history characterizes a southern Rocky Mountain subalpine forest. *Canadian Journal of Forest Research*, **42(9)**, 1649-1660.

Deutsch, C.A., Tewksbury, J.J., Huey, R.B., Sheldon, K.S., Ghalambor, C.K., Haak, D.C., and Martin, P.R., 2008: Impacts of climate warming on terrestrial ectotherms across latitude. *Proceedings of the National Academy of Sciences*, **105(18)**, 6668-6672.

Devi, N., Hagedorn, F., Moiseev, P., Bugmann, H., Shiyatov, S., Mazepa, V., and Rigling, A., 2008: Expanding forests and changing growth forms of Siberian larch at the Polar Urals treeline during the 20th century. *Global Change Biology*, **14(7)**, 1581-1591.

Devictor, V., van Swaay, C., Brereton, T., Brotons, L., Chamberlain, D., Heliola, J., Herrando, S., Julliard, R., Kuussaari, M., Lindstrom, A., Reif, J., Roy, D.B., Schweiger, O., Settele, J., Stefanescu, C., Van Strien, A., Van Turnhout, C., Vermouzek, Z., WallisDeVries, M., Wynhoff, I., and Jiguet, F., 2012: Differences in the climatic debts of birds and butterflies at a continental scale. *Nature Climate Change*, **2(2)**, 121-124.

Dial, R.J., Berg, E.E., Timm, K., McMahon, A., and Geck, J., 2007: Changes in the alpine forest-tundra ecotone commensurate with recent warming in southcentral Alaska: Evidence from orthophotos and field plots. *J. Geophys. Res.*, **112(G4)**, G04015.

Dieleman, W.I.J., Vicca, S., Dijkstra, F.A., Hagedorn, F., Hovenden, M.J., Larsen, K.S., Morgan, J.A., Volder, A., Beier, C., Dukes, J.S., King, J., Leuzinger, S., Linder, S., Luo, Y., Oren, R., De Angelis, P., Tingey, D., Hoosbeek, M.R., and Janssens, I.A., 2012: Simple additive effects are rare: a quantitative review of plant biomass and soil process responses to combined manipulations of CO2 and temperature. *Global Change Biology*, **18(9)**, 2681-2693.

Diez, J.M., D'Antonio, C.M., Dukes, J.S., Grosholz, E.D., Olden, J.D., Sorte, C.J.B., Blumenthal, D.M., Bradley, B.A., Early, R., Ibanez, I., Jones, S.J., Lawler, J.J., and Miller, L.P., 2012: Will extreme climatic events facilitate biological invasions? *Frontiers in Ecology and the Environment*, **10(5)**, 249-257.

Diffenbaugh, N.S., and Giorgi, F., 2012: Climate change hotspots in the CMIP5 global climate model ensemble. *Climatic Change*, **114(3-4)**, 813-822.

Diffenbaugh, N.S., Pal, J.S., Trapp, R.J., and Giorgi, F., 2005: Fine-scale processes regulate the response of extreme events to global climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **102(44)**, 15774-15778.

Dise, N.B., 2009: Peatland Response to Global Change. *Science*, **326(5954)**, 810-811.

Doak, D.F., and Morris, W.F., 2010: Demographic compensation and tipping points in climate-induced range shifts. *Nature*, **467(7318)**, 959-962.

Dobrowski, S.Z., Abatzoglou, J., Swanson, A.K., Greenberg, J.A., Mynsberge, A.R., Holden, Z.A., and Schwartz, M.K., 2013: The climate velocity of the contiguous United States during the 20th century. *Global Change Biology*, **19(1)**, 241-251.

Dohrenbusch, A., and Bolte, A., 2007: Forest plantations. In *Wood production, wood technology and biotechnological impacts.* [U. Kües (ed.)]. Universitätsverlag Göttingen, Göttingen, Germany, pp. 73-83.

Donnelly, A., Caffarra, A., Kelleher, C.T., O'Neill, B.F., Diskin, E., Pletsers, A., Proctor, H., Stirnemann, R., O'Halloran, J., Penuelas, J., Hodkinson, T.R., and Sparks, T.H., 2012: Surviving in a warmer world: environmental and genetic responses. *Climate Research,* **53(3)**, 245-262.

Doughty, C.E., Field, C.B., and McMillan, A.M.S., 2011: Can crop albedo be increased through modification of leaf trichomes, and could this cool the regional climate? *Climatic Change,* **104(2)**, 379-387.

Doughty, C.E., and Goulden, M.L., 2008: Are tropical forests near a high temperature threshold? *Journal of Geophysical Research-Biogeosciences,* **113**.

Doxford, S.W., and Freckleton, R.P., 2012: Changes in the large-scale distribution of plants: extinction, colonisation and the effects of climate. *Journal of Ecology,* **100(2)**, 519-529.

Drake, J.E., Gallet-Budynek, A., Hofmockel, K.S., Bernhardt, E.S., Billings, S.A., Jackson, R.B., Johnsen, K.S., Lichter, J., McCarthy, H.R., McCormack, M.L., Moore, D.J.P., Oren, R., Palmroth, S., Phillips, R.P., Pippen, J.S., Pritchard, S.G., Treseder, K.K., Schlesinger, W.H., DeLucia, E.H., and Finzi, A.C., 2011: Increases in the flux of carbon belowground stimulate nitrogen uptake and sustain the long-term enhancement of forest productivity under elevated CO2. *Ecology Letters,* **14(4)**, 349-357.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.I., Knowler, D.J., Leveque, C., Naiman, R.J., Prieur-Richard, A.H., Soto, D., Stiassny, M.L.J., and Sullivan, C.A., 2006: Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews,* **81(2)**, 163-182.

Dukes, J.S., Pontius, J., Orwig, D., Garnas, J.R., Rodgers, V.L., Brazee, N., Cooke, B., Theoharides, K.A., Stange, E.E., Harrington, R., Ehrenfeld, J., Gurevitch, J., Lerdau, M., Stinson, K., Wick, R., and Ayres, M., 2009: Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: What can we predict? *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere,* **39(2)**, 231-248.

Dulamsuren, C., Hauck, M., Nyambayar, S., Bader, M., Osokhjargal, D., Oyungerel, S., and Leuschner, C., 2009: Performance of Siberian elm (Ulmus pumila) on steppe slopes of the northern Mongolian mountain taiga: Drought stress and herbivory in mature trees. *Environmental and Experimental Botany,* **66(1)**, 18-24.

Dullinger, S., Gattringer, A., Thuiller, W., Moser, D., Zimmermann, N.E., Guisan, A., Willner, W., Plutzar, C., Leitner, M., Mang, T., Caccianiga, M., Dirnbock, T., Ertl, S., Fischer, A., Lenoir, J., Svenning, J.C., Psomas, A., Schmatz, D.R., Silc, U., Vittoz, P., and Hulber, K., 2012: Extinction debt of high-mountain plants under twenty-first-century climate change. *Nature Climate Change,* **2(8)**, 619-622.

Dunn, R.R., Harris, N.C., Colwell, R.K., Koh, L.P., and Sodhi, N.S., 2009: The sixth mass coextinction: are most endangered species parasites and mutualists? *Proceedings of the Royal Society B-Biological Sciences,* **276(1670)**, 3037-3045.

Duquesnay, A., Breda, N., Stievenard, M., and Dupouey, J.L., 1998: Changes of tree-ring delta C-13 and water use efficiency of beech (Fagus sylvatica L.) in north-eastern France during the past century. . *Plant Cell and Environment,* **21**, 565-572.

Durance, I., and Ormerod, S.J., 2007: Climate change effects on upland stream macroinvertebrates over a 25-year period. *Global Change Biology,* **13(5)**, 942-957.

Eamus, D., and Palmer, A.R., 2008: Is climate change a possible explanation for woody thickening in arid and semi-arid regions? *International Journal of Ecology,* **2007**.

Eastaugh, C.S., Potzelsberger, E., and Hasenauer, H., 2011: Assessing the impacts of climate change and nitrogen deposition on Norway spruce (Picea abies L. Karst) growth in Austria with BIOME-BGC. *Tree Physiology,* **31(3)**, 262-274.

Edburg, S.L., Hicke, J.A., Brooks, P.D., Pendall, E.G., Ewers, B.E., Norton, U., Gochis, D., Gutmann, E.D., and Meddens, A.J.H., 2012: Cascading impacts of bark beetle-caused tree mortality on coupled biogeophysical and biogeochemical processes. *Frontiers in Ecology and the Environment,* **10(8)**, 416-424.

Eggermont, H., Verschuren, D., Audenaert, L., Lens, L., Russell, J., Klaassen, G., and Heiri, O., 2010: Limnological and ecological sensitivity of Rwenzori mountain lakes to climate warming. *Hydrobiologia,* **648(1)**, 123-142.

Eisenhauer, N., Cesarz, S., Koller, R., Worm, K., and Reich, P.B., 2012: Global change belowground: impacts of elevated CO2, nitrogen, and summer drought on soil food webs and biodiversity. *Global Change Biology,* **18(2)**, 435-447.

Eliseev, A.V., and Mokhov, I.I., 2011: Effect of including land-use driven radiative forcing of the surface albedo of land on climate response in the 16th-21st centuries. *Izvestiya Atmospheric and Oceanic Physics,* **47(1)**, 15-30.

Ellery, W.N., Scholes, R.J., and Mentis, M.T., 1991: An initial approach to predicting the sensitivity of the South African grassland biome to climate change. *South African Journal of Science*, **87**, 499-503.

Elmendorf, S.C., Henry, G.H.R., Hollister, R.D., Bjork, R.G., Boulanger-Lapointe, N., Cooper, E.J., Cornelissen, J.H.C., Day, T.A., Dorrepaal, E., Elumeeva, T.G., Gill, M., Gould, W.A., Harte, J., Hik, D.S., Hofgaard, A., Johnson, D.R., Johnstone, J.F., Jonsdottir, I.S., Jorgenson, J.C., Klanderud, K., Klein, J.A., Koh, S., Kudo, G., Lara, M., Levesque, E., Magnusson, B., May, J.L., Mercado-Diaz, J.A., Michelsen, A., Molau, U., Myers-Smith, I.H., Oberbauer, S.F., Onipchenko, V.G., Rixen, C., Martin Schmidt, N., Shaver, G.R., Spasojevic, M.J., orhallsdottir, o.E., Tolvanen, A., Troxler, T., Tweedie, C.E., Villareal, S., Wahren, C.-H., Walker, X., Webber, P.J., Welker, J.M., and Wipf, S., 2012: Plot-scale evidence of tundra vegetation change and links to recent summer warming. *Nature Clim. Change*, **advance online publication**.

Elser, J.J., Andersen, T., Baron, J.S., Bergström, A.K., Jansson, M., Kyle, M., Nydick, K.R., Steger, L., and Hessen, D.O., 2009: Shifts in Lake N:P Stoichiometry and Nutrient Limitation Driven by Atmospheric Nitrogen Deposition. *Science*, **326(5954)**, 835-837.

Elser, J.J., Bracken, M.E.S., Cleland, E.E., Gruner, D.S., Harpole, W.S., Hillebrand, H., Ngai, J.T., Seabloom, E.W., Shurin, J.B., and Smith, J.E., 2007: Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. *Ecology Letters*, **10**, 1135-1142.

Emmett, B.A., Beier, C., Estiarte, M., Tietema, A., Kristensen, H.L., Williams, D., Penuelas, J., Schmidt, I., and Sowerby, A., 2004: The response of soil processes to climate change: Results from manipulation studies of shrublands across an environmental gradient. *Ecosystems*, **7(6)**, 625-637.

Engler, R., Randin, C.F., Thuiller, W., Dullinger, S., Simmermann, N.E., Araujo, M.B., Pearman, P.B., Le Lay, G., Peidallu, C., Albert, C.H., Choler, P., Coldea, G., De Lamo, S., Dirnbock, T., Gegout, J.C., Gomez-Garcia, D., Grytnes, J.A., Heegaard, E., Hoistad, F., Nogues-Bravo, D., Normand, S., Puscas, M., Sebastia, M.T., Stanisci, A., Theurillat, J.P., Trivedi, M.R., Vittoz, P., and Guisan, A., 2011: 21st century climate change threatens mountain flora unequally across Europe. *Global Change Biology*, **17(7)**, 2330-2341.

Enquist, B.J., and Enquist, C.A.F., 2011: Long-term change within a Neotropical forest: assessing differential functional and floristic responses to disturbance and drought. *Global Change Biology*, **17(3)**, 1408-1424.

Epstein, H., Kaplan, J., Lischke, H., and Yu, Q., 2007: Simulating future changes in arctic tundra and sub-arctic vegetation. *Computing in Science and Engineering*, **9**, 12-23.

Epstein, H.E., D. A. Walker, M. K. Raynolds, G. J. Jia, and A. M. Kelley, 2008: Phytomass patterns across a temperature gradient of the North American arctic tundra. *Journal of Geophysical Research*, **113**.

Erisman, J.W., Galloway, J., Seitzinger, S., Bleeker, A., and Butterbach-Bahl, K., 2011: Reactive nitrogen in the environment and its effect on climate change. *Current Opinion in Environmental Sustainability*, **3(5)**, 281-290.

Erskine, P.D., Lamb, D., and Bristow, M., 2006: Tree species diversity and ecosystem function: Can tropical multi-species plantations generate greater productivity? *Forest Ecology and Management*, **233(2–3)**, 205-210.

Essl, F., Dullinger, S., Moser, D., Rabitsch, W., and Kleinbauer, I., 2012: Vulnerability of mires under climate change: implications for nature conservation and climate change adaptation. *Biodiversity and Conservation*, **21(3)**, 655-669.

EU Council, 1992: *Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora.* 66 pp.

Euskirchen, E.S., McGuire, A.D., Chapin III, F.S., Yi, S., and Thompson, C.C., 2009: Changes in vegetation in northern Alaska under scenarios of climate change, 2003-2100: implications for climate feedbacks. *Ecological Applications*, **19(4)**, 1022-1043.

Eycott, A.E., Stewart, G.B., Buyung-Ali, L.M., Bowler, D.E., Watts, K., and Pullin, A.S., 2012: A meta-analysis on the impact of different matrix structures on species movement rates. *Landscape Ecology*, **27(9)**, 1263-1278.

Fahey, T.J., 1998: Recent Changes in an Upland Forest in South-Central New York. *Journal of the Torrey Botanical Society*, **125(1)**, 51-59.

Fall, S., Niyogi, D., Gluhovsky, A., Pielke, R.A., Kalnay, E., and Rochon, G., 2010: Impacts of land use land cover on temperature trends over the continental United States: assessment using the North American Regional Reanalysis. *International Journal of Climatology*, **30(13)**, 1980-1993.

Falloon, P.D., Dankers, R., Betts, R.A., Jones, C.D., Booth, B.B.B., and Lambert, F.H., 2012: Role of vegetation change in future climate under the A1B scenario and a climate stabilisation scenario, using the HadCM3C earth systems model. *Biogeosciences*, **9(11)**, 4739-4756.

FAO, 2005: *Forestry Paper 147* Global Forest Resources Assessment. Series 147, 350 pp.

FAO, 2010a: *Global Forest Resources Assessment 2010.* FAO Forestry Paper Series 163, Rome, Italy, 340 pp.

FAO, 2010b: *Global Forest Resources Assessment 2010.* Rome, Italy, 12 pp.

Fargione, J., 2011: ENERGY Boosting biofuel yields. *Nature Climate Change,* **1(9)**, 445-446.

Farquhar, G.D., von Caemmerer, S., and Berry, J.A., 1980: A biochemical model of photosynthetic CO2 assimilation in leaves of C3 species. *Planta,* **149**, 78-90.

Fay, P.A., Carlisle, J.D., Knapp, A.K., Blair, J.M., and Collins, S.L., 2003: Productivity Responses to Altered Rainfall Patterns in a C-4-Dominated Grassland. *Oecologia,* **137(2)**, 245-251.

Fay, P.A., Kaufman, D.M., Nippert, J.B., Carlisle, J.D., and Harper, C.W., 2008: Changes in grassland ecosystem function due to extreme rainfall events: implications for responses to climate change. *Global Change Biology,* **14(7)**, 1600-1608.

Fearnside, P.M., 2005: Do hydroelectric dams mitigate global warming? The case of Brazil's Curua-Una Dam. *Mitigation and Adaptation Strategies for Global Change,* **10**, 675-691.

Feeley, K.J., and Rehm, E.M., 2012: Amazon's vulnerability to climate change heightened by deforestation and man-made dispersal barriers. *Global Change Biology,* **18(12)**, 3606-3614.

Fellows, A.W., and Goulden, M.L., 2012: Rapid vegetation redistribution in Southern California during the early 2000s drought. *Journal of Geophysical Research: Biogeosciences,* **117(G3)**, G03025.

Fensham, R.J., Fairfax, R.J., and Dwyer, J.M., 2012: Potential aboveground biomass in drought-prone forest used for rangeland pastoralism. *Ecological Applications,* **22(3)**, 894-908.

Fensham, R.J., Fairfax, R.J., and Ward, D.P., 2009: Drought-induced tree death in savanna. *Global Change Biology,* **15**, 380-387.

Fensholt, R., Langanke, T., Rasmussen, K., Reenberg, A., Prince, S.D., Tucker, C., Scholes, B., Le, Q.B., Bondeau, A., Eastman, R., Epstein, H., Gaughan, A.E., Hellden, U., Mbow, C., Olsson, L., Paruelo, J., Schweitzer, C., Seaquist, J., and Wessels, K., 2012: Greenness in semi-arid areas across the globe 1981-2007 - an Earth Observing Satellite based analysis of trends and drivers. *Remote Sensing of Environment,* **121**, 144-158.

Ferriere, R., and Legendre, S., 2013: Eco-evolutionary feedbacks, adaptive dynamics and evolutionary rescue theory. *Philosophical Transactions of the Royal Society B-Biological Sciences,* **368(1610)**.

Ficke, A.D., Myrick, C.A., and Hansen, L.J., 2007: Potential impacts of global climate change on freshwater fisheries. *Reviews in Fish Biology and Fisheries,* **17(4)**, 581-613.

Field, C.B., Lobell, D.B., Peters, H.A., and Chiariello, N.R., 2007: Feedbacks of terrestrial ecosystems to climate change. *Annual Review of Environment and Resources,* **32**, 1-29.

Findell, K.L., Shevliakova, E., Milly, P.C.D., and Stouffer, R.J., 2007: Modeled impact of anthropogenic land cover change on climate. *Journal of Climate,* **20(14)**, 3621-3634.

Finzi, A.C., Norby, R.J., Calfapietra, C., Gallet-Budynek, A., Gielen, B., Holmes, W.E., Hoosbeek, M.R., Iversen, C.M., Jackson, R.B., Kubiske, M.E., Ledford, J., Liberloo, M., Oren, R., Polle, A., Pritchard, S., Zak, D.R., Schlesinger, W.H., and Ceulemans, R., 2007: Increases in nitrogen uptake rather than nitrogen-use efficiency support higher rates of temperate forest productivity under elevated CO_2. *Proceedings of the National Academy of Sciences,* **104(35)**, 14014-14019.

Fiorese, G., and Guariso, G., 2013: Modeling the role of forests in a regional carbon mitigation plan. *Renewable Energy,* **52**, 175-182.

Fischer, J., and Lindenmayer, D.B., 2007: Landscape modification and habitat fragmentation: a synthesis. *Global Ecology and Biogeography,* **16(3)**, 265-280.

Fischlin, A., Midgley, G.F., Price, J.T., Leemans, R., Gopal, B., urley, C., Rounsevell, M.D.A., Dube, O.P., Tarazona, J., and Velichko, A.A., 2007: Ecosystems, their properties, goods, and services. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In *Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson (eds.)]. Cambridge University Press, Cambridge, pp. 211-272.

Fisher, J.B., Hurtt, G., Thomas, R.Q., and Chambers, J.Q., 2008: Clustered disturbances lead to bias in large-scale estimates based on forest sample plots. *Ecology Letters,* **11(6)**, 554-563.

Fisher, R., McDowell, N., Purves, D., Moorcroft, P., Sitch, S., Cox, P., Huntingford, C., Meir, P., and Ian Woodward, F., 2010: Assessing uncertainties in a second-generation dynamic vegetation model caused by ecological scale limitations. *New Phytologist,* **187(3)**, 666-681.

FLUXNET, 2012: Historical Site Status, from http://fluxnet.ornl.gov/site_status.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., and Holling, C.S., 2004: Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology Evolution and Systematics*, **35**, 557-581.

Forbes, B.C., Fauria, M.M., and Zetterberg, P., 2010: Russian Arctic warming and ‘greening’ are closely tracked by tundra shrub willows. *Global Change Biology*, **16(5)**, 1542-1554.

Fordham, D.A., Akcakaya, H.R., Araujo, M.B., Elith, J., Keith, D.A., Pearson, R., Auld, T.D., Mellin, C., Morgan, J.W., Regan, T.J., Tozer, M., Watts, M.J., White, M., Wintle, B.A., Yates, C., and Brook, B.W., 2012: Plant extinction risk under climate change: are forecast range shifts alone a good indicator of species vulnerability to global warming? *Global Change Biology*, **18(4)**, 1357-1371.

Franklin, J., Davis, F.W., Ikegami, M., Syphard, A.D., Flint, L.E., Flint, A.L., and Hannah, L., 2013: Modeling plant species distributions under future climates: how fine scale do climate projections need to be? *Global Change Biology*, **19(2)**, 473-483.

Franks, S.J., and Hoffmann, A.A., 2012: Genetics of Climate Change Adaptation. *Annual Review of Genetics, Vol 46*, **46**, 185-208.

Franks, S.J., and Weis, A.E., 2008: A change in climate causes rapid evolution of multiple life-history traits and their interactions in an annual plant. *Journal of Evolutionary Biology*, **21(5)**, 1321-1334.

Frelich, L.E., Peterson, R.O., Dovciak, M., Reich, P.B., Vucetich, J.A., and Eisenhauer, N., 2012: Trophic cascades, invasive species and body-size hierarchies interactively modulate climate change responses of ecotonal temperate-boreal forest. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **367(1605)**, 2955-2961.

Frolking, S., Talbot, J., Jones, M.C., Treat, C.C., Kauffman, J.B., Tuittila, E.S., and Roulet, N., 2011: Peatlands in the Earth's 21st century climate system. *Environmental Reviews*, **19**, 371-396.

Gagen, M., Finsinger, W., Wagner-Cremer, F., McCarroll, D., Loader, N.J., Robertson, I., Jalkanen, R., Young, G., and Kirchhefer, A., 2011: Evidence of changing intrinsic water-use efficiency under rising atmospheric CO2 concentrations in Boreal Fennoscandia from subfossil leaves and tree ring δ13C ratios. *Global Change Biology*, **17(2)**, 1064-1072.

Galiano, L., Martínez-Vilalta, J., and Lloret, F., 2010: Drought-Induced Multifactor Decline of Scots Pine in the Pyrenees and Potential Vegetation Change by the Expansion of Co-occurring Oak Species. *Ecosystems*, **13(7)**, 978-991.

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z.C., Freney, J.R., Martinelli, L.A., Seitzinger, S.P., and Sutton, M.A., 2008: Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. *Science*, **320(5878)**, 889-892.

Ganey, J.L., and Vojta, S.C., 2011: Tree mortality in drought-stressed mixed-conifer and ponderosa pine forests, Arizona, USA. *Forest Ecology and Management*, **261(1)**, 162-168.

Gao, J., and Liu, Y., 2011: Climate warming and land use change in Heilongjiang Province, Northeast China. *Applied Geography*, **31(2)**, 476-482.

Gao, X.J., and Giorgi, F., 2008: Increased aridity in the Mediterranean region under greenhouse gas forcing estimated from high resolution simulations with a regional climate model. *Global and Planetary Change*, **62(3-4)**, 195-209.

Garcia-Carreras, L., and Parker, D.J., 2011: How does local tropical deforestation affect rainfall? *Geophysical Research Letters*, **38(19)**, L19802.

Garcia-Carreras, L., Parker, D.J., Taylor, C.M., Reeves, C.E., and Murphy, J.G., 2010: Impact of mesoscale vegetation heterogeneities on the dynamical and thermodynamic properties of the planetary boundary layer. *Journal of Geophysical Research*, **115**, D03102.

Garreta, V., Miller, P.A., Guiot, J., Hely, C., Brewer, S., Sykes, M.T., and Litt, T., 2010: A method for climate and vegetation reconstruction through the inversion of a dynamic vegetation model. *Climate Dynamics*, **35(2-3)**, 371-389.

Garrity, S.R., C.D., A., McDowell, N., and Cai, M., in review: Two decades of climate-related tree mortality in the forests and woodlands of northern New Mexico, USA. *Ecological Applications*.

Gaudnik, C., Corcket, E., Clement, B., Delmas, C.E.L., Gombert-Courvoisier, S., Muller, S., Stevens, C.J., and Alard, D., 2011: Detecting the footprint of changing atmospheric nitrogen deposition loads on acid grasslands in the context of climate change. *Global Change Biology*, **17(11)**, 3351-3365.

Gedalof, Z., and Berg, A.A., 2010: Tree ring evidence for limited direct CO2 fertilization of forests over the 20th century. *Global Biogeochemical Cycles*, **24(GB3027)**, 1-6.

Giardina, C.P., and Ryan, M.G., 2000: Evidence that decomposition rates of organic carbon in mineral soil do not vary with temperature. *Nature,* **404(6780)**, 858-861.

Gibson, D.J., and Hulbert, L.C., 1987: Effects of Fire, Topography and Year-to-Year Climatic Variation on Species Composition in Tallgrass Prairie. *Vegetatio,* **72(3)**, 175 -185.

Gibson, L., Lee, T.M., Koh, L.P., Brook, B.W., Gardner, T.A., Barlow, J., Peres, C.A., Bradshaw, C.J.A., Laurance, W.F., Lovejoy, T.E., and Sodhi, N.S., 2011: Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature,* **478(7369)**, 378.

Gienapp, P., Lof, M., Reed, T.E., McNamara, J., Verhulst, S., and Visser, M.E., 2013: Predicting demographically sustainable rates of adaptation: can great tit breeding time keep pace with climate change? *Philosophical Transactions of the Royal Society B-Biological Sciences,* **368(1610)**.

Gienapp, P., Teplitsky, C., Alho, J.S., Mills, J.A., and Merila, J., 2008: Climate change and evolution: disentangling environmental and genetic responses. *Molecular Ecology,* **17(1)**, 167-178.

Gill, A.M., Wionarski, J.Z., and York, A., 1999: *Australians biodiversity responses to fire: Plants, birds and invertebrates*. Commonwealth Department of the Environment and Heritage, Canberra, Australia, 267 pp.

Gill, J.L., Williams, J.W., Jackson, S.T., Lininger, K.B., and Robinson, G.S., 2009: Pleistocene Megafaunal Collapse, Novel Plant Communities, and Enhanced Fire Regimes in North America. *Science,* **326(5956)**, 1100-1103.

Gillingham, P.K., Huntley, B., Kunin, W.E., and Thomas, C.D., 2012: The effect of spatial resolution on projected responses to climate warming. *Diversity and Distributions,* **18(10)**, 990-1000.

Girardin, M.P., and Mudelsee, M., 2008: Past and future changes in Canadian boreal wildfire activity. *Ecological Applications,* **18(2)**, 391-406.

Goetz, S.J., Epstein, H.E., Bhatt, U., Jia, G.J., Kaplan, J.O., Lischke, H., Yu, Q., Bunn, A., Lloyd, A., Alcaraz, D., Beck, P.S.A., Comiso, J., Raynolds, M.K., and Walker, D.A., 2011: Recent changes in Arctic vegetation: satellite observations and simulation model predictions. In *Eurasian Arctic Land Cover and Land Use in a Changing Climate* [G. Gutman & A. Reissell (eds.)]. Springer-Verlag, Amsterdam, pp. 9-36.

Goetz, S.J., Mack, M.C., Gurney, K.R., Randerson, J.T., and Houghton, R.A., 2007: Ecosystem responses to recent climate change and fire disturbance at northern high latitudes: observations and model results contrasting northern Eurasia and North America. *Environmental Research Letters,* **2 (4)**.

Goldblum, D., and Rigg, L.S., 2010: The deciduous forest – boreal forest ecotone. *Geography Compass,* **4(7)**, 701-717.

Golding, N., and Betts, R., 2008: Fire risk in Amazonia due to climate change in the HadCM3 climate model: Potential interactions with deforestation. *Global Biogeochemical Cycles,* **22(4)**, 1-10.

Gonzalez, P., 2001: Desertification and a shift of forest species in the West African Sahel. *Climate Research,* **17(2)**, 217-228.

Gonzalez, P., Neilson, R.P., Lenihan, J.M., and Drapek, R.J., 2010: Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change. *Global Ecology and Biogeography,* **19(6)**, 755-768.

Gonzalez, P., Tucker, C.J., and Sy, H., 2012: Tree density and species decline in the African Sahel attributable to climate. *Journal of Arid Environments,* **78(0)**, 55-64.

Good, P., Caesar, J., Bernie, D., Lowe, J.A., van der Linden, P., Gosling, S.N., Warren, R., Arnell, N.W., Smith, S., Bamber, J., Payne, T., Laxon, S., Srokosz, M., Sitch, S., Gedney, N., Harris, G., Hewitt, H., Jackson, L., Jones, C.D., O'Connor, F., Ridley, J., Vellinga, M., Halloran, P., and McNeall, D., 2011: A review of recent developments in climate change science. Part I: Understanding of future change in the large-scale climate system. *Progress in Physical Geography,* **35(3)**, 281-296.

Good, P., Jones, C., Lowe, J., Betts, R., and Gedney, N., 2013: Comparing Tropical Forest Projections from Two Generations of Hadley Centre Earth System Models, HadGEM2-ES and HadCM3LC. *Journal of Climate,* **26(2)**, 495-511.

Gordo, O., 2007: Why are bird migration dates shifting? A review of weather and climate effects on avian migratory phenology. *Climate Research,* **35(1-2)**, 37-58.

Gordo, O., and Sanz, J.J., 2005: Phenology and climate change: a long-term study in a Mediterranean locality. *Oecologia,* **146(3)**, 484-495.

Gordo, O., and Sanz, J.J., 2009: Long-term temporal changes of plant phenology in the Western Mediterranean. *Global Change Biology,* **15(8)**, 1930-1948.

Gottfried, M., Pauli, H., Futschik, A., Akhalkatsi, M., Barancok, P., Alonso, J.L.B., Coldea, G., Dick, J., Erschbamer, B., Calzado, M.R.F., Kazakis, G., Krajci, J., Larsson, P., Mallaun, M., Michelsen, O., Moiseev, D., Moiseev, P., Molau, U., Merzouki, A., Nagy, L., Nakhutsrishvili, G., Pedersen, B., Pelino, G., Puscas, M., Rossi, G., Stanisci, A., Theurillat, J.P., Tomaselli, M., Villar, L., Vittoz, P., Vogiatzakis, I., and Grabherr, G., 2012: Continent-wide response of mountain vegetation to climate change. *Nature Climate Change*, **2(2)**, 111-115.

Graiprab, P., Pongput, K., Tangtham, N., and Gassman, P.W., 2010: Hydrologic evaluation and effect of climate change on the At Samat watershed, Northeastern Region, Thailand. *International Agricultural Engineering Journal*, **19(2)**, 12-22.

Green, R.E., Collingham, Y.C., Willis, S.G., Gregory, R.D., Smith, K.W., and Huntley, B., 2008: Performance of climate envelope models in retrodicting recent changes in bird population size from observed climatic change. *Biology Letters*, **4(5)**, 599-602.

Griesbauer, H.P., and Green, D.S., 2012: Geographic and temporal patterns in white spruce climate–growth relationships in Yukon, Canada. *Forest Ecology and Management*, **267**, 215-227.

Grime, J.P., Fridley, J.D., Askew, A.P., Thompson, K., Hodgson, J.G., and Bennet, C.R., 2008: Long-term resistance to simulated climate change in an infertile grassland. *Proceeding of the National Academy of Science*, **105(29)**, 10028-10032.

Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., and Briggs, J.M., 2008: Global Change and the Ecology of Cities. *Science*, **319(5864)**, 756-760.

Grosse, G., Harden, J., Turetsky, M., McGuire, A.D., Camill, P., Tarnocai, C., Frolking, S., Schuur, E.A.G., Jorgenson, T., Marchenko, S., Romanovsky, V., Wickland, K.P., French, N., Waldrop, M., Bourgeau-Chavez, L., and Striegl, R.G., 2011: Vulnerability of high-latitude soil organic carbon in North America to disturbance. *Journal of Geophysical Research-Biogeosciences*, **116**.

Gruber, N., and Galloway, J.N., 2008: An Earth-system perspective of the global nitrogen cycle. *Nature*, **451(7176)**, 293-296.

Gunderson, A.R., and Leal, M., 2012: Geographic variation in vulnerability to climate warming in a tropical Caribbean lizard. *Functional Ecology*, **26(4)**, 783-793.

Gunderson, C.A., Edwards, N.T., Walker, A.V., O'Hara, K.H., Campion, C.M., and Hanson, P.J., 2012: Forest phenology and a warmer climate - growing season extension in relation to climatic provenance. *Global Change Biology*, **18(6)**, 2008-2025.

Gunderson, L., and Holling, C.S. (eds.), 2001: *Panarchy: Understanding Transformations in Systems of Humans and Nature*. Island Press, pp. 507.

Gyllström, M., Hansson, L.A., Jeppesen, E., Garcia-Criado, F., Gross, E., Irvine, K., Kairesalo, T., Kornijow, R., Miracle, M.R., Nykanen, M., Noges, T., Romo, S., Stephen, D., Van Donk, E., and Moss, B., 2005: The role of climate in shaping zooplankton communities of shallow lakes. *Limnology and Oceanography*, **50(6)**, 2008-2021.

Hague, M.J., Ferrari, M.R., Miller, J.R., Patterson, D.A., Russell, G.L., Farrell, A.P., and Hinch, S.G., 2011: Modelling the future hydroclimatology of the lower Fraser River and its impacts on the spawning migration survival of sockeye salmon. *Global Change Biology*, **17(1)**, 87-98.

Haider, S., Kueffer, C., Edwards, P.J., and Alexander, J.M., 2012: Genetically based differentiation in growth of multiple non-native plant species along a steep environmental gradient. *Oecologia*, **170(1)**, 89-99.

Hall, J.S., Ashton, M.S., Garen, E.J., and Jose, S., 2011: The ecology and ecosystem services of native trees: Implications for reforestation and land restoration in Mesoamerica. *Forest Ecology and Management*, **261(10)**, 1553-1557.

Halley, J.M., Iwasa, Y., and Vokou, D., 2013: Comment on "Extinction Debt and Windows of Conservation Opportunity in the Brazilian Amazon". *Science*, **339(6117)**, 271.

Hamilton, S.K., 2010: Biogeochemical implications of climate change for tropical rivers and floodplains. *Hydrobiologia*, **657(1)**, 19-35.

Hampe, A., 2011: Plants on the move: The role of seed dispersal and initial population establishment for climate-driven range expansions. *Acta Oecologica-International Journal of Ecology*, **37(6)**, 666-673.

Han, S.J., Xu, D., and Wang, S.L., 2012: Decreasing potential evaporation trends in China from 1956 to 2005: Accelerated in regions with significant agricultural influence? *Agricultural and Forest Meteorology*, **154-155**, 44-56.

Hannah, L., 2012: *Saving a Million Species: Extinction Risk from Climate Change*. Island Press, Washington Covelo London, 419 pp.

Hannah, L., Midgley, G., Andelman, S., Araujo, M., Hughes, G., Martinez-Meyer, E., Pearson, R., and Williams, P., 2007: Protected area needs in a changing climate. *Frontiers in Ecology and the Environment,* **5(3)**, 131-138.

Hansen, M.M., Olivieri, I., Waller, D.M., Nielsen, E.E., and Grp, G.W., 2012: Monitoring adaptive genetic responses to environmental change. *Molecular Ecology,* **21(6)**, 1311-1329.

Hanson, P.J., Wullschleger, S.D., Norby, R.J., Tschaplinski, T.J., and Gunderson, C.A., 2005: Importance of changing CO2, temperature, precipitation, and ozone on carbon and water cycles of an upland oak forest: incorporating experimental results into model simulations. *Global Change Biology,* **11**, 1402-1423.

Hari, P., and Kulmata, L., 2008: *Boreal Forest and Climate Change*. Springer, New York, 582 pp.

Harris, J.A., Hobbs, R.J., Higgs, E., and Aronson, J., 2006: Ecological Restoration and Global Climate Change. *Restoration Ecology,* **14**, 170-176.

Harrison, S.P., and Goni, M.F.S., 2010: Global patterns of vegetation response to millennial-scale variability and rapid climate change during the last glacial period. *Quaternary Science Reviews,* **29(21-22)**, 2957-2980.

Hartmann, D., Klein Tank, A., and others, in press: Observations: Atmosphere and Surface. In *The Physical Science Basis: Contribution of Working Group 1 to the 5th Assessment Report of the Intergovernmental Panel on Climate Change* [T. F. Stocker (ed.)]. pp.

Hastings, A., 2004: Transients: the key to long-term ecological understanding? *Trends in Ecology & Evolution,* **19(1)**, 39-45.

Haxeltine, A., and Prentice, I.C., 1996: BIOME3: an equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability, and competition among plant functional types. *Global Biogeochemical Cycles,* **10**, 693-709.

Hayes, F., Jones, M.L.M., Mills, G., and Ashmore, M., 2007: Meta-analysis of the relative sensitivity of semi-natural vegetation species to ozone. *Environmental Pollution,* **146(3)**, 754-762.

Haywood, A.M., Ridgwell, A., Lunt, D.J., Hill, D.J., Pound, M.J., Dowsett, H.J., Dolan, A.M., Francis, J.E., and Williams, M., 2011: Are there pre-Quaternary geological analogues for a future greenhouse warming? *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences,* **369(1938)**, 933-956.

Haywood, A.M., and Valdes, P.J., 2006: Vegetation cover in a warmer world simulated using a dynamic global vegetation model for the Mid-Pliocene. *Palaeogeography Palaeoclimatology Palaeoecology,* **237(2-4)**, 412-427.

He, J.J., Ju, J.H., Wen, Z.P., Lu, J.M., and Jin, Q.H., 2007: A review of recent advances in research on Asian monsoon in China. *Advances in Atmospheric Sciences,* **24(6)**, 972-992.

Heckenberger, M.J., Russell, J.C., Toney, J.R., and Schmidt, M.J., 2007: The legacy of cultural landscapes in the Brazilian Amazon: implications for biodiversity. *Philosophical Transactions of the Royal Society B-Biological Sciences,* **362(1478)**, 197-208.

Hegarty, M.J., 2012: Invasion of the hybrids. *Molecular Ecology,* **21(19)**, 4669-4671.

Hegglin, M.I., and Shepherd, T.G., 2009: Large climate-induced changes in ultraviolet index and stratosphere-to-troposphere ozone flux. *Nature Geoscience,* **10(10)**, 687- 691.

Hegland, S.J., Nielsen, A., Lazaro, A., Bjerknes, A.L., and Totland, 2009: How does climate warming affect plant-pollinator interactions? *Ecology Letters,* **12(2)**, 184-195.

Hellden, U., and Tottrup, C., 2008: Regional desertification: A global synthesis. *Global and Planetary Change,* **64(3-4)**, 169-176.

Heller, N.E., and Zavaleta, E.S., 2009: Biodiversity management in the face of climate change: A review of 22 years of recommendations. *Biological Conservation,* **142(1)**, 14-32.

Hellmann, J.J., Byers, J.E., Bierwagen, B.G., and Dukes, J.S., 2008: Five potential consequences of climate change for invasive species. *Conservation Biology,* **22(3)**, 534-543.

Hemery, G.E., 2008: Forest management and silvicultural responses to projected climate change impacts on European broadleaved trees and forests. *International Forestry Review,* **10(4)**, 591-607.

Hermoso, V., and Clavero, M., 2011: Threatening processes and conservation management of endemic freshwater fish in the Mediterranean basin: a review. *Marine and Freshwater Research,* **62(3)**, 244-254.

Heubes, J., Kühn, I., König, K., Wittig, R., Zizka, G., and Hahn, K., 2011: Modelling biome shifts and tree cover change for 2050 in West Africa. *Journal of Biogeography,* **38(12)**, 2248-2258.

Hewitt, N., Klenk, N., Smith, A.L., Bazely, D.R., Yan, N., Wood, S., MacLellan, J.I., Lipsig-Mumme, C., and Henriques, I., 2011: Taking stock of the assisted migration debate. *Biological Conservation,* **144(11)**, 2560-2572.

Hickler, T., Eklundh, L., Seaquist, J.W., Smith, B., Ardo, J., Olsson, L., Sykes, M.T., and SjÃ¶strÃ¶m, M., 2005: Precipitation controls Sahel greening trend. *Geophysical Research Letters,* **32(L21415)**, 1-4.

Hickler, T., Smith, B., Prentice, I.C., Mjöfors, K., Miller, P., Arneth, A., and Sykes, M.T., 2008: CO_2 fertilization in temperate FACE experiments not representative of boreal and tropical forests. *Global Change Biology,* **14**, 1531-1542.

Hickler, T., Vohland, K., Feehan, J., Miller, P.A., Smith, B., Costa, L., Giesecke, T., Fronzek, S., Carter, T.R., Cramer, W., Kühn, I., and Sykes, M.T., 2012: Projecting the future distribution of European potential natural vegetation zones with a generalized, tree species-based dynamic vegetation model. *Global Ecology and Biogeography,* **21(1)**, 50-63.

Higgins, S.I., Clark, J.S., Nathan, R., Hovestadt, T., Schurr, F., Fragoso, J.M.V., Aguiar, M.R., Ribbens, E., and Lavorel, S., 2003: Forecasting plant migration rates: managing uncertainty for risk assessment. *Journal of Ecology,* **91(3)**, 341-347.

Higgins, S.I., and Scheiter, S., 2012: Atmospheric CO2 forces abrupt vegetation shifts locally, but not globally. *Nature,* **488(7410)**, 209-212.

Higuera, P.E., Chipman, M.L., Barnes, J.L., Urban, M.A., and Hu, F.S., 2011: Variability of tundra fire regimes in Arctic Alaska: millennial-scale patterns and ecological implications. *Ecological Applications,* **21(8)**, 3211-3226.

Hill, P.W., Farrar, J., Roberts, P., Farrell, M., Grant, H., Newsham, K.K., Hopkins, D.W., Bardgett, R.D., and Jones, D.L., 2011: Vascular plant success in a warming Antarctic may be due to efficient nitrogen acquisition. *Nature Clim. Change,* **1(1)**, 50-53.

Hinzman, L.D., Bettez, N.D., Bolton, W.R., Chapin III, F.S., Dyurgerov, M.B., Fastie, C.L., Griffith, B., Hollister, R.D., Hope, A., Huntington, H.P., Jensen, A.M., Jia, G.J., Jorgenson, T., Kane, D.L., Klein, D.R., Kofinas, G., Lynch, A.H., Lloyd, A.H., McGuire, A.D., Nelson, F.E., Oechel, W.C., Osterkamp, T.E., Racine, C.H., Romanovsky, V.E., Stone, R.S., Stow, D.A., Sturm, M., Tweedie, C.E., Vourlitis, G.L., Walker, M.D., Walker, D.A., Webber, P.J., Welker, J.M., Winker, K., and Yoshikawa, K., 2005: Evidence and implications of recent climate change in northern Alaska and other arctic regions. *Climatic Change,* **72(3)**, 251-298.

Hockey, P.A.R., Sirami, C., Ridley, A.R., Midgley, G.F., and Babiker, H.A., 2011: Interrogating recent range changes in South African birds: confounding signals from land use and climate change present a challenge for attribution. *Diversity and Distributions,* **17(2)**, 254-261.

Hodgson, J.A., Thomas, C.D., Dytham, C., Travis, J.M.J., and Cornell, S.J., 2012: The Speed of Range Shifts in Fragmented Landscapes. *PLoS One,* **7(10)**.

Hoegh-Guldberg, O., Hughes, L., McIntyre, S., Lindenmayer, D.B., Parmesan, C., Possingham, H.P., and Thomas, C.D., 2008: Assisted colonization and rapid climate change. *Science,* **321(5887)**, 345-346.

Hof, C., Levinsky, I., Araujo, M.B., and Rahbek, C., 2011: Rethinking species' ability to cope with rapid climate change. *Global Change Biology,* **17(9)**, 2987-2990.

Hoffmann, A.A., and Sgro, C.M., 2011: Climate change and evolutionary adaptation. *Nature,* **470(7335)**, 479-485.

Hofmann, G.E., and Todgham, A.E., 2010: Living in the Now: Physiological Mechanisms to Tolerate a Rapidly Changing Environment. *Annual Review of Physiology,* **72**, 127-145.

Hofmockel, K.S., Zak, D.R., Moran, K.K., and Jastrow, J.D., 2011: Changes in forest soil organic matter pools after a decade of elevated CO2 and O3. *Soil Biology and Biochemistry,* **43(7)**, 1518-1527.

Hogg, E.H., Brandt, J.P., and Michaelian, M., 2008: Impact of a regional drought on the productivity, dieback and biomass of western Canadian aspen forests. *Canadian Journal of Forest Research,* **38**, 1373–1384, doi:1310.1139/X1308-1001.

Hole, D.G., Huntley, B., Arinaitwe, J., Butchart, S.H.M., Collingham, Y.C., Fishpool, L.D.C., Pain, D.J., and Willis, S.G., 2011: Toward a Management Framework for Networks of Protected Areas in the Face of Climate Change. *Conservation Biology,* **25(2)**, 305-315.

Hole, D.G., Willis, S.G., Pain, D.J., Fishpool, L.D., Butchart, S.H.M., Collingham, Y.C., Rahbek, C., and Huntley, B., 2009: Projected impacts of climate change on a continent-wide protected area network. *Ecology Letters,* **12(5)**, 420-431.

Holling, C.S., 1973: Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics,* **4**, 1-23.

Holmgren, M., Stapp, P., Dickman, C.R., Gracia, C., Graham, S., Gutiérrez, J.R., Hice, C., Jaksic, F., Kelt, D.A., Letnic, M., Lima, M., López, B.C., Meserve, P.L., Milstead, W.B., Polis, G.A., Previtali, M.A., Richter, M., Sabaté, S., and Squeo, F.A., 2006: Extreme climatic events shape arid and semiarid ecosystems. *Frontiers in Ecology and the Environment,* **4(2)**, 87-95.

Hooijer, A., Page, S., Canadell, J.G., Silvius, M., Kwadijk, J., Wosten, H., and Jauhiainen, J., 2010: Current and future CO(2) emissions from drained peatlands in Southeast Asia. *Biogeosciences*, **7(5)**, 1505-1514.

Hoover, S.E.R., Ladley, J.J., Shchepetkina, A.A., Tisch, M., Gieseg, S.P., and Tylianakis, J.M., 2012: Warming, CO2, and nitrogen deposition interactively affect a plant-pollinator mutualism. *Ecology Letters*, **15(3)**, 227-234.

Horowitz, L.W., 2006: Past present and future concentrations of tropospheric ozone and aerosols: morthodology, ozone evaluation, and sensitivity to aerosol wet removal. *Journal of Geophysical Research - Atmospheres,* **111(D22211)**, 1-16.

Høye, T.T., Post, E., Meltofte, H., Schmidt, N.M., and Forchhammer, M.C., 2007: Rapid advancement of spring in the High Arctic. *Current biology : CB*, **17(12)**, R449-R451.

Huang, D., Haack, R.A., and Zhang, R., 2011: Does global warming increase establishment rates of invasive alien species? A Centurial time series analysis. *PLoS One*, **6(9)**, 1-5.

Huang, J.G., Bergeron, Y., Denneler, B., Berninger, F., and Tardif, J., 2007: Response of forest trees to increased atmospheric CO2. *Critical Reviews in Plant Sciences*, **26(5-6)**, 265-283.

Hudson, I.L., and Keatley, M.R. (eds.), 2010: *Phenological Research*. Springer Dordrecht, Heidelberg, London, New York, pp. 522.

Huey, R.B., Kearney, M.R., Krockenberger, A., Holtum, J.A.M., Jess, M., and Williams, S.E., 2012: Predicting organismal vulnerability to climate warming: roles of behaviour, physiology and adaptation. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **367(1596)**, 1665-1679.

Hughes, R.F., Archer, S.R., Asner, G.P., Wessman, C.A., McMurtry, C.H.A.D., Nelson, J.I.M., and Ansley, R.J., 2006: Changes in aboveground primary production and carbon and nitrogen pools accompanying woody plant encroachment in a temperate savanna. *Global Change Biology*, **12(9)**, 1733-1747.

Hülber, K., Winkler, M., and Grabherr, G., 2010: Intraseasonal climate and habitat-specific variability controls the flowering phenology of high alpine plant species. *Functional Ecology*, **24(2)**, 245-252.

Hunter, C.M., Caswell, H., Runge, M.C., Regehr, E.V., Amstrup, S.C., and Stirling, I., 2010: Climate change threatens polar bear populations: a stochastic demographic analysis. *Ecology*, **91(10)**, 2883-2897.

Huntingford, C., Cox, P.M., Mercado, L.M., Sitch, S., Bellouin, N., Boucher, O., and Gedney, N., 2011: Highly contrasting effects of different climate forcing agents on terrestrial ecosystem services. *Philosophical Transactions of the Royal Society A-Mathematical, Physical and Engineering Sciences*, **369(1943)**, 2026-2037.

Huntingford, C., Zelazowski, P., Galbraith, D., Mercado, L.M., Sitch, S., Fisher, R., Lomas, M., P.Walker, A., Jones, C.D., Booth, B.B.B., Malhi, Y., Hemming, D., Kay, G., Good, P., Lewis, S.L., Phillips, O.L., Atkin, O.K., Lloyd, J., Gloor, E., Zaragoza-Castells, J., Meir, P., Betts, R., Harris, P.P., Nobre, C., Marengo, J., and Cox, P.M., 2013: High resilience of tropical rainforests to climate change. *Nature Geoscience*.

Huntington, H.P., Goodstein, E., and Euskirchen, E., 2012: Towards a tipping point in responding to change: rising costs, fewer options for Arctic and global societies. *Ambio*, **41(1)**, 66-74.

Hurtt, G.C., Chini, L.P., Frolking, S., Betts, R.A., Feddema, J., Fischer, G., Fisk, J.P., Hibbard, K., Houghton, R.A., Janetos, A., Jones, C.D., Kindermann, G., Kinoshita, T., Goldewijk, K.K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., Vuuren, D.P.v., and Wang, Y.P., 2011: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Climatic Change*, **109**, 117-161.

Husby, A., Visser, M.E., and Kruuk, L.E.B., 2011: Speeding Up Microevolution: The Effects of Increasing Temperature on Selection and Genetic Variance in a Wild Bird Population. *Plos Biology*, **9(2)**.

Hyvönen, R., Ågren, G.I., Linder, S., Persson, T., Cotrufo, M.F., Ekblad, A., Freeman, M., Grelle, A., Janssens, I.A., Jarvis, P.G., Kellomäki, S., Lindroth, A., Loustau, D., Lundmark, T., Norby, R.J., Oren, R., Pilegaard, K., Ryan, M.G., Sigurdsson, B.D., Strömgren, M., Oijen, M.V., and Wallin, G., 2007: The likely impact of elevated [CO2], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: a literature review. *New Phytologist*, **173(3)**, 463-480.

Ihlow, F., Dambach, J., Engler, J.O., Flecks, M., Hartmann, T., Nekum, S., Rajaei, H., and Rodder, D., 2012: On the brink of extinction? How climate change may affect global chelonian species richness and distribution. *Global Change Biology*, **18(5)**, 1520-1530.

Innes, J.L., 1992: Observations on the Condition of Beech (Fagus sylvatica L.) in Britain in 1990. *Forestry*, **65(1)**, 35-60.

Inouye, D.W., 2008: Effects of climate change on phenology, frost damage, and floral abundance of montane wildflowers. *Ecology*, **89(2)**, 353-362.

INPE, 2012: Projeto Desmatamento (PRODES): Monitoramento da Floresta Amazonica por Satelite, 2009, from http://www.obt.inpe.br/prodes/.

IPCC, 2012: Summary for Policymakers. In *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor & P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 1-19.

Iverson, L., Prasad, A., and Matthews, S., 2008: Modeling potential climate change impacts on the trees of the northeastern United States. *Mitigation and Adaptation Strategies for Global Change,* **13(5-6)**, 487-516.

Iverson, L.R., Prasad, A.M., Matthews, S.N., and Peters, M.P., 2011: Lessons Learned While Integrating Habitat, Dispersal, Disturbance, and Life-History Traits into Species Habitat Models Under Climate Change. *Ecosystems,* **14(6)**, 1005-1020.

Iverson, L.R., Schwartz, M.W., and Prasad, A.M., 2004: How fast and far might tree species migrate in the eastern United States due to climate change? *Global Ecology and Biogeography,* **13(3)**, 209-219.

Jackson, S., and Weng, C. (1999). *Late quaternary extinction of a tree species in eastern North America.* Paper presented at the National Academy of Sciences USA.

Jackson, S.T., Gray, S.T., and Shuman, B., 2009: Paleoecology and resource management in a dynamic landscape: case studies from the Rocky Mountain headwaters. In *Conservation Paleobiology: Using the Past to Manage for the Future* [G. P. Dietl & K. W. Flessa (eds.)]. The Paleontological Society, pp. 61-80.

Jackson, S.T., and Hobbs, R.J., 2009: Ecological Restoration in the Light of Ecological History. *Science,* **325(5940)**, 567-569.

Jackson, S.T., and Overpeck, J.T., 2000: Responses of Plant Populations and Communities to Environmental Changes of the Late Quaternary. *Paleobiology,* **26(4)**, 194-220.

Jansen, E., J.T., O., and others, 2007: Chapter 6: Paleoclimate. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [S. Solomon & e. al (eds.)]. Cambridge University Press. Cambridge, Cambridge, pp. 433-497.

Jaramillo, C., Ochoa, D., Contreras, L., Pagani, M., Carvajal-Ortiz, H., Pratt, L.M., Krishnan, S., Cardona, A., Romero, M., Quiroz, L., Rodriguez, G., Rueda, M.J., de la Parra, F., Moron, S., Green, W., Bayona, G., Montes, C., Quintero, O., Ramirez, R., Mora, G., Schouten, S., Bermudez, H., Navarrete, R., Parra, F., Alvaran, M., Osorno, J., Crowley, J.L., Valencia, V., and Vervoort, J., 2010: Effects of Rapid Global Warming at the Paleocene-Eocene Boundary on Neotropical Vegetation. *Science,* **330(6006)**, 957-961.

Jarvis, P.G., 1976: The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. *Philosophical Transactions of the Royal Society of London,* **B. 273**, 593-610.

Jenkins, K.M., and Boulton, A.J., 2007: Detecting impacts and setting restoration targets in arid-zone rivers: aquatic micro-invertebrate responses to reduced floodplain inundation. *Journal of Applied Ecology,* **44(4)**, 823-832.

Jensen, K.D., Beier, C., Michelsen, A., and Emmett, B.A., 2003: Effects of experimental drought on microbial processes in two temperate heathlands at contrasting water conditions. *Applied Soil Ecology,* **24(2)**, 165-176.

Jeong, S.J., Ho, C.H., Gim, H.J., and Brown, M.E., 2011: Phenology shifts at start vs. end of growing season in temperate vegetation over the Northern Hemisphere for the period 1982-2008. *Global Change Biology,* **17(7)**, 2385-2399.

Jeppesen, E., Moss, B., Bennion, H., Carvalho, L., DeMeester, L., Feuchtmayr, H., Friberg, N., Gessner, M.O., Hefting, M., Lauridsen, T.L., Liboriussen, L., Malmquist, H.J., May, L., Meerhoff, M., Olafsson, J.S., Soons, M.B., and Verhoeven, J.T.A., 2010: Interaction of Climate Change and Eutrophication. In *Climate Change Impacts on Freshwater Ecosystems*. Wiley-Blackwell, pp. 119-151.

Jia, B., Ma, Y., and Qiu, K., 2009a: Dynamics of the vegetation coverage in recent 15 years in Yijinhuoluo County, Inner Mongolia, China. . *Arid Land Geography,* **32(4)**, 481-487.

Jia, G.J., Epstein, H.E., and Walker, D.A., 2009b: Vegetation greening in the canadian arctic related to decadal warming. *Journal of Environmental Monitoring,* **11(12)**, 2231-2238.

Jin, J., Lu, S., Li, S., and Miller, N.L., 2010: Impact of Land Use Change on the Local Climate over the Tibetan Plateau. *Advances in Meteorology,* **2010(ID 837480)**, 1-6.

Jin, Y., Randerson, J.T., Goetz, S.J., Beck, P.S.A., Loranty, M.M., and Goulden, M.L., 2012: The influence of burn severity on postfire vegetation recovery and albedo change during early succession in North American boreal forests. *Journal of Geophys. Research Biogeosciences,* **117(G1)**, G01036, doi:01010.01029/02011jg001886.

Johanson, C.M., and Fu, Q., 2009: Hadley Cell Widening: Model Simulations versus Observations. *Journal of Climate*, **22(10)**, 2713-2725.

Johnk, K.D., Huisman, J., Sharples, J., Sommeijer, B., Visser, P.M., and Stroom, J.M., 2008: Summer heatwaves promote blooms of harmful cyanobacteria. *Global Change Biology*, **14(3)**, 495-512.

Johnson, W.C., Millett, B.V., Gilmanov, T., Voldseth, R.A., Guntenspergen, G.R., and Naugle, D.E., 2005: Vulnerability of northern prairie wetlands to climate change. *Bioscience*, **55(10)**, 863-872.

Johnstone, J.F., Hollingsworth, T.N., Chapin, F.S., and Mack, M.C., 2010: Changes in fire regime break the legacy lock on successional trajectories in Alaskan boreal forest. *Global Change Biology*, **16(4)**, 1281-1295.

Jones, C.D., Cox, P., and Huntingford, C., 2003: Uncertainty in climate-carbon-cycle projections associated with the sensitivity of soil respiration to temperature. *Tellus Series B-Chemical and Physical Meteorology*, **55(2)**, 642-648.

Jones, C.D., Hughes, J.K., Bellouin, N., Hardiman, S.C., Jones, G.S., Knight, J., Liddicoat, S., O'Connor, F.M., Andres, R.J., Bell, C., Boo, K.O., Bozzo, A., Butchart, N., Cadule, P., Corbin, K.D., Doutriaux-Boucher, M., Friedlingstein, P., Gornall, J., Gray, L., Halloran, P.R., Hurtt, G., Ingram, W.J., Lamarque, J.F., Law, R.M., Meinshausen, M., Osprey, S., Palin, E.J., Chini, L.P., Raddatz, T., Sanderson, M.G., Sellar, A.A., Schurer, A., Valdes, P., Wood, N., Woodward, S., Yoshioka, M., and Zerroukat, M., 2011: The HadGEM2-ES implementation of CMIP5 centennial simulations. *Geoscientific Model Development*, **4(3)**, 543-570.

Jongman, R.H.G., Bouwma, I.M., Griffioen, A., Jones-Walters, L., and Van Doorn, A.M., 2011: The Pan European Ecological Network: PEEN. *Landscape Ecology*, **26(3)**, 311-326.

Jorgenson, M.T., Romanovsky, V., Harden, J., Shur, Y., O'Donnell, J., Schuur, E.A.G., Kanevskiy, M., and Marchenko, S., 2010: Resilience and vulnerability of permafrost to climate change. *Canadian Journal of Forest Research*, **40(7)**, 1219-1236.

Joubert, D.F., Rothauge, A., and Smit, G.N., 2008: A conceptual model of vegetation dynamics in the semiarid Highland savanna of Namibia, with particular reference to bush thickening by Acacia mellifera. *Journal of Arid Environments*, **72(12)**, 2201-2210.

Jump, A.S., Hunt, J.M., Martinez-Izquierdo, J.A., and Penuelas, J., 2006: Natural selection and climate change: temperature-linked spatial and temporal trends in gene frequency in Fagus sylvatica. *Molecular Ecology*, **15(11)**, 3469-3480.

Jump, A.S., PeÑUelas, J., Rico, L., Ramallo, E., Estiarte, M., MartÍNez-Izquierdo, J.A., and Lloret, F., 2008: Simulated climate change provokes rapid genetic change in the Mediterranean shrub Fumana thymifolia. *Global Change Biology*, **14(3)**, 637-643.

Jung, M., Reichstein, M., Ciais, P., Seneviratne, S.I., Sheffield, J., Goulden, M.L., Bonan, G., Cescatti, A., Chen, J.Q., de Jeu, R., Dolman, A.J., Eugster, W., Gerten, D., Gianelle, D., Gobron, N., Heinke, J., Kimball, J., Law, B.E., Montagnani, L., Mu, Q.Z., Mueller, B., Oleson, K., Papale, D., Richardson, A.D., Roupsard, O., Running, S., Tomelleri, E., Viovy, N., Weber, U., Williams, C., Wood, E., Zaehle, S., and Zhang, K., 2010: Recent decline in the global land evapotranspiration trend due to limited moisture supply. *Nature*, **467(7318)**, 951-954.

Kaiser, K.E., McGlynn, B.L., and Emanuel, R.E., 2012: Ecohydrology of an outbreak: mountain pine beetle impacts trees in drier landscape positions first. *Ecohydrology*, n/a-n/a.

Kane, J.M., Meinhardt, K.A., Chang, T., Cardall, B.L., Michalet, R., and Whitham, T.G., 2011: Drought-induced mortality of a foundation species (Juniperus monosperma) promotes positive afterlife effects in understory vegetation. *Plant Ecology*, **212(5)**, 733-741.

Kanniah, K.D., Beringer, J., North, P., and Hutley, L., 2012: Control of atmospheric particles on diffuse radiation and terrestrial plant productivity. *Progress in Physical Geography*, **36(2)**, 209-237.

Kappes, H., and Haase, P., 2012: Slow, but steady: dispersal of freshwater molluscs. *Aquatic Sciences*, **74(1)**, 1-14.

Karell, P., Ahola, K., Karstinen, T., Valkama, J., and Brommer, J.E., 2011: Climate change drives microevolution in a wild bird. *Nature Communications*, **2**, 1-7.

Karnosky, D.F., Pregitzer, K.S., Zak, D.R., Kubiske, M.E., Hendrey, G.R., Weinstein, D., Nosal, M., and Percy, K.E., 2005: Scaling ozone responses of forest trees to the ecosystem level in a changing climate. *Plant Cell and Environment*, **28(8)**, 965-981.

Kasischke, E.S., Verbyla, D.L., Rupp, T.S., McGuire, A.D., Murphy, K.A., Jandt, R., Barnes, J.L., Hoy, E.E., Duffy, P.A., Calef, M., and Turetsky, M.R., 2010: Alaska's changing fire regime — implications for the vulnerability of its boreal forests. *Canadian Journal of Forest Research*, **40(7)**, 1313-1324.

Kasson, M.T., and Livingston, W.H., 2012: Relationships among beech bark disease, climate, radial growth response and mortality of American beech in northern Maine, USA. *Forest Pathology*, **42(3)**, 199-212.

Kaufman, D.S., Schneider, D.P., McKay, N.P., Ammann, C.M., Bradley, R.S., Briffa, K.R., Miller, G.H., Otto-Bliesner, B.L., Overpeck, J.T., Vinther, B.M., and Arctic Lakes 2k Project, M., 2009: Recent Warming Reverses Long-Term Arctic Cooling. *Science,* **325(5945)**, 1236-1239.

Kaushal, S.S., Likens, G.E., Jaworski, N.A., Pace, M.L., Sides, A.M., Seekell, D., Belt, K.T., Secor, D.H., and Wingate, R.L., 2010: Rising stream and river temperatures in the United States. *Frontiers in Ecology and the Environment,* **8(9)**, 461-466.

Kearney, M., Porter, W.P., Williams, C., Ritchie, S., and Hoffmann, A.A., 2009: Integrating biophysical models and evolutionary theory to predict climatic impacts on species' ranges: the dengue mosquito Aedes aegypti in Australia. *Functional Ecology,* **23(3)**, 528-538.

Kearney, M.R., Wintle, B.A., and Porter, W.P., 2010: Correlative and mechanistic models of species distribution provide congruent forecasts under climate change. *Conservation Letters,* **3(3)**, 203-213.

Keenan, T., Maria Serra, J., Lloret, F., Ninyerola, M., and Sabate, S., 2011: Predicting the future of forests in the Mediterranean under climate change, with niche- and process-based models: CO2 matters! *Global Change Biology,* **17(1)**, 565-579.

Keith, D.A., Akcakaya, H.R., Thuiller, W., Midgley, G.F., Pearson, R.G., Phillips, S.J., Regan, H.M., Araujo, M.B., and Rebelo, T.G., 2008: Predicting extinction risks under climate change: coupling stochastic population models with dynamic bioclimatic habitat models. *Biology Letters,* **4(5)**, 560-563.

Kelly, A.E., and Goulden, M.L., 2008: Rapid shifts in plant distribution with recent climate change. *Proceedings of the National Academy of Sciences of the United States of America,* **105(33)**, 11823-11826.

Ketola, T., Kellermann, V., Kristensen, T.N., and Loeschcke, V., 2012: Constant, cycling, hot and cold thermal environments: strong effects on mean viability but not on genetic estimates. *Journal of Evolutionary Biology,* **25(6)**, 1209-1215.

Kgope, B.S., Bond, W.J., and Midgley, G.F., 2010: Growth responses of African savanna trees implicate atmospheric [CO2] as a driver of past and current changes in savanna tree cover. *Austral Ecology,* **35(4)**, 451-463.

Kharuk, V.I., Ranson, K.J., Oskorbin, P.A., Im, S.T., and Dvinskaya, M.L., 2013: Climate induced birch mortality in Trans-Baikal lake region, Siberia. *Forest Ecology and Management,* **289(0)**, 385-392.

Khoury, C., Laliberte, B., and Guarino, L., 2010: Trends in ex situ conservation of plant genetic resources: a review of global crop and regional conservation strategies. *Genetic Resources and Crop Evolution,* **57(4)**, 625-639.

Kiesecker, J.M., 2011: Global stressors and the global decline of amphibians: tipping the stress immunocompetency axis. *Ecological Research,* **26(5)**, 897-908.

Kindermann, G.E., McCallum, I., Fritz, S., and et al., 2008: A global forest growing stock, biomass and carbon map based on FAO statistics. *Silva Fennica.,* **42(3)**, 387-396.

Kinlan, B.P., and Gaines, S.D., 2003: Propagule dispersal in marine and terrestrial environments: A community perspective. *Ecology,* **84(8)**, 2007-2020.

Kint, V., Aertsen, W., Campioli, M., Vansteenkiste, D., Delcloo, A., and Muys, B., 2012: Radial growth change of temperate tree species in response to altered regional climate and air quality in the period 1901-2008. *Climatic Change,* **115(2)**, 343-363.

Kirdyanov, A.V., Hagedorn, F., Knorre, A.A., Fedotova, E.V., Vaganov, E.A., Naurzbaev, M.M., Moiseev, P.A., and Rigling, A., 2012: 20th century tree-line advance and vegetation changes along an altitudinal transect in the Putorana Mountains, northern Siberia. *Boreas,* **41(1)**, 56-67.

Kirilenko, A.P., and Sedjo, R.A., 2007: Climate change impacts on forestry. *Proceedings of the National Academy of Sciences of the United States of America,* **104(50)**, 19697-19702.

Kirschbaum, M.U.F., 2004: Soil respiration under prolonged soil warming: are rate reductions caused by acclimation or substrate loss? *Global Change Biology,* **10(11)**, 1870-1877.

Kirschbaum, M.U.F., Saggar, S., Tate, K.R., Giltrap, D.L., Ausseil, A.-G.E., Greenhalgh, S., and Whitehead, D., 2012: Comprehensive evaluation of the climate-change implications of shifting land use between forest and grassland: New Zealand as a case study. *Agriculture, Ecosystems & Environment,* **150**, 123-138.

Kirwan, M.L., and Blum, L.K., 2011: Enhanced decomposition offsets enhanced productivity and soil carbon accumulation in coastal wetlands responding to climate change. *Biogeosciences,* **8(4)**, 987-993.

Klausmeyer, K.R., and Shaw, M.R., 2009: Climate Change, Habitat Loss, Protected Areas and the Climate Adaptation Potential of Species in Mediterranean Ecosystems Worldwide. *PLoS One,* **4(7)**, 1-9.

KleinGoldewijk, K., 2001: Estimating global land use change over the past 300 years: The HYDE database. *Global Biogeochemical Cycles,* **5(2)**, 417-433.

Klingberg, J., Engardt, M., Uddling, J., Karlsson, P.E., and Pleijel, H., 2011: Ozone risk for vegetation in the future climate of Europe based on stomatal ozone uptake calculations. *Tellus Series a-Dynamic Meteorology and Oceanography,* **63(1)**, 174-187.

Klos, R.J., Wang, G.G., Bauerle, W.L., and Rieck, J.R., 2009: Drought impact on forest growth and mortality in the southeast USA: an analysis using Forest Health and Monitoring data. *Ecological Applications,* **19(3)**, 699-708.

Knapp, A.K., Beier, C., Briske, D.D., Classen, A.T., Luo, Y., Reichstein, M., Smith, M.D., Smith, S.D., Bell, J.E., Fay, P.A., Heisler, J.L., Leavitt, S.W., Sherry, R., Smith, B., and Weng, E., 2008a: Consequences of More Extreme Precipitation Regimes for Terrestrial Ecosystems. *Bioscience,* **58(9)**, 811-821.

Knapp, A.K., Briggs, J.M., Collins, S.L., Archer, S.R., Bret-Harte, M.S., Ewers, B.E., and Peters, D.P., 2007: Shrub encroachment in North American grasslands: shifts in growth form dominance rapidly alters control of ecosystem carbon inputs. *Global Change Biology,* **14(3)**, 615-623.

Knapp, S., Kühn, I., Wittig, R., Ozinga, W.A., Poschlod, P., and Klotz, S., 2008b: Urbanization causes shifts in species' trait state frequencies. *Preslia,* **80(4)**, 375-388.

Knohl, A., and Baldocchi, D.D., 2008: Effects of diffuse radiation on canopy gas exchange processes in a forest ecosystem. *Journal of Geophysical Research,* **113(G02023)**.

Knops, J.M.H., Naeemw, S., and Reich, P.B., 2007: The impact of elevated CO2, increased nitrogen availability and biodiversity on plant tissue quality and decomposition. *Global Change Biology,* **13(9)**, 1960-1971.

Knorr, W., Prentice, I.C., House, J.I., and Holland, E.A., 2005: Long-term sensitivity of soil carbon turnover to warming. *Nature,* **433(7023)**, 298-301.

Knox, R., Bisht, G., Wang, J., and Bras, R., 2011: Precipitation Variability over the Forest-to-Nonforest Transition in Southwestern Amazonia. *Journal of Climate,* **24**, 2368-2377.

Knudsen, E., Linden, A., Both, C., Jonzen, N., Pulido, F., Saino, N., Sutherland, W.J., Bach, L.A., Coppack, T., Ergon, T., Gienapp, P., Gill, J.A., Gordo, O., Hedenstroom, A., Lehikoinen, E., Marra, P.P., Moller, A.P., Nilsson, A.L.K., Peron, G., Ranta, E., Rubolini, D., Sparks, T.H., Spina, F., Studds, C.E., Saether, S.A., Tryjanowski, P., and Stenseth, N.C., 2011: Challenging claims in the study of migratory birds and climate change. *Biological Reviews,* **86(4)**, 928-946.

Knutti, R., and Sedlacek, J., 2012: Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Clim. Change,* **advance online publication**.

Koehler, I.H., Poulton, P.R., Auerswald, K., and Schnyder, H., 2010: Intrinsic water-use efficiency of temperate seminatural grassland has increased since 1857: an analysis of carbon isotope discrimination of herbage from the Park Grass Experiment. *Global Change Biology,* **16(5)**, 1531-1541.

Konarzewski, T.K., Murray, B.R., and Godfree, R.C., 2012: Rapid Development of Adaptive, Climate-Driven Clinal Variation in Seed Mass in the Invasive Annual Forb Echium plantagineum L. *PLoS One,* **7(12)**.

Kongstad, J., Schmidt, I.K., Riis-Nielsen, T., Arndal, M.F., Mikkelsen, T.N., and Beier, C., 2012: High Resilience in Heathland Plants to Changes in Temperature, Drought, and CO2 in Combination: Results from the CLIMAITE Experiment. *Ecosystems,* **15(2)**, 269-283.

Körner, C., Asshoff, R., Bignucolo, O., Hattenschwiler, S., Keel, S.G., Pelaez-Riedl, S., Pepin, S., Siegwolf, R.T.W., and Zotz, G., 2005: Carbon flux and growth in mature deciduous forest trees exposed to elevated CO2. *Science,* **309(5739)**, 1360-1362.

Körner, C., and Basler, D., 2010: Phenology Under Global Warming. *Science,* **327(5972)**, 1461-1462.

Körner, C., Morgan, J.A., and Norby, R., 2007: CO_2 fertilisation: when, where, how much? In *Terrestrial ecosystems in a changing world* [S. G. Canadell, D. E. Pataki & L. F. Pitelka (eds.)]. Springer, Berlin Heidelberg, pp. 9-22.

Koutavas, A., 2008: Late 20th century growth acceleration in greek firs (Abies cephalonica) from Cephalonia Island, Greece: A CO2 fertilization effect? *Dendrochronologia,* **26(1)**, 13-19.

Kovach-Orr, C., and Fussmann, G.F., 2013: Evolutionary and plastic rescue in multitrophic model communities. *Philosophical Transactions of the Royal Society B-Biological Sciences,* **368(1610)**.

Kraft, N.J.B., Metz, M.R., Condit, R.S., and Chave, J., 2010: The relationship between wood density and mortality in a global tropical forest data set. *New Phytologist,* **188(4)**, 1124-1136.

Kramer, K., Bijlsma, R.J., Hickler, T., and Thuiller, W., 2012: Why Would Plant Species Become Extinct Locally If Growing Conditions Improve? *International Journal of Biological Sciences,* **8(8)**, 1121-1129.

Kramer, K., Degen, B., Buschbom, J., Hickler, T., Thuiller, W., Sykes, M.T., and de Winter, W., 2010: Modelling exploration of the future of European beech (Fagus sylvatica L.) under climate change-Range, abundance, genetic diversity and adaptive response. *Forest Ecology and Management,* **259(11)**, 2213-2222.

Kremer, A., Ronce, O., Robledo-Arnuncio, J.J., Guillaume, F., Bohrer, G., Nathan, R., Bridle, J.R., Gomulkiewicz, R., Klein, E.K., Ritland, K., Kuparinen, A., Gerber, S., and Schueler, S., 2012: Long-distance gene flow and adaptation of forest trees to rapid climate change. *Ecology Letters*, **15(4)**, 378-392.

Kriegler, E., Hall, J.W., Held, H., Dawson, R., and Schellnhuber, H.J., 2009: Imprecise probability assessment of tipping points in the climate system. *Proceedings of the National Academy of Sciences of the United States of America*, **106(13)**, 5041-5046.

Kropelin, S., Verschuren, D., Lezine, A.M., Eggermont, H., Cocquyt, C., Francus, P., Cazet, J.P., Fagot, M., Rumes, B., Russell, J.M., Darius, F., Conley, D.J., Schuster, M., von Suchodoletz, H., and Engstrom, D.R., 2008: Climate-driven ecosystem succession in the Sahara: The past 6000 years. *Science*, **320(5877)**, 765-768.

Kudo, G., Amagai, Y., Hoshino, B., and Kaneko, M., 2011: Invasion of dwarf bamboo into alpine snow-meadows in northern Japan: pattern of expansion and impact on species diversity. *Ecology and Evolution*, **1(1)**, 85-96.

Kukowski, K., Schwinning, S., and Schwartz, B., 2012: Hydraulic responses to extreme drought conditions in three co-dominant tree species in shallow soil over bedrock. *Oecologia*, 1-12.

Kuldna, P., Peterson, K., Poltimae, H., and Luig, J., 2009: An application of DPSIR framework to identify issues of pollinator loss. *Ecological Economics*, **69(1)**, 32-42.

Kullman, L., and Öberg, L., 2009: Post-Little Ice Age tree line rise and climate warming in the Swedish Scandes: a landscape ecological perspective. *Journal of Ecology*, **97(3)**, 415-429.

Kundzewicz, Z.W., Mata, L.J., Arnell, N.W., Döll, P., Kabat, P., Jiménez, B., Miller, K.A., Oki, T., Sen, Z., and Shiklomanov, I.A., 2007: Freshwater resources and their management. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In *Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson (eds.)]. Cambridge University Press, Cambridge, pp. 173-210.

Kunkel, K.E., Easterling, D.R., Hubbard, K., and Redmond, K., 2004: Temporal variations in frost-free season in the United States: 1895-2000. *Geophysical Research Letters*, **31(3)**.

Kuparinen, A., Savolainen, O., and Schurr, F.M., 2010: Increased mortality can promote evolutionary adaptation of forest trees to climate change. *Forest Ecology and Management*, **259(5)**, 1003-1008.

Kurz, W.A., Dymond, C.C., Stinson, G., Rampley, G.J., Neilson, E.T., Carroll, A.L., Ebata, T., and Safranyik, L., 2008: Mountain pine beetle and forest carbon feedback to climate change. *Nature*, **452(7190)**, 987-990.

Kusano, T., and Inoue, M., 2008: Long-Term Trends toward Earlier Breeding of Japanese Amphibians. *Journal of Herpetology*, **42(4)**, 608-614.

Kuussaari, M., Bommarco, R., Heikkinen, R.K., Helm, A., Krauss, J., Lindborg, R., Ockinger, E., Partel, M., Pino, J., Roda, F., Stefanescu, C., Teder, T., Zobel, M., and Steffan-Dewenter, I., 2009: Extinction debt: a challenge for biodiversity conservation. *Trends in Ecology & Evolution*, **24(10)**, 564-571.

Kvalevåg, M.M., and Myhre, G., 2007: Human Impact on Direct and Diffuse Solar Radiation during the Industrial Era. *Journal of Climate*, **20(19)**, 4874-4883.

La Sorte, F.A., and Jetz, W., 2010: Avian distributions under climate change: towards improved projections. *Journal of Experimental Biology*, **213(6)**, 862-869.

Lambert, A.M., Miller-Rushing, A.J., and Inouye, D.W., 2010: Changes in Snowmelt Date and Summer Precipitation Affect the Flowering Phenology of Erythronium Grandiflorum (Glacier Lily; Liliaceae). *American Journal of Botany*, **97(9)**, 1431-1437.

Lambin, E.F., and Meyfroidt, P., 2011: Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences of the United States of America*, **108(9)**, 3465-3472.

Lane, J.E., Kruuk, L.E.B., Charmantier, A., Murie, J.O., and Dobson, F.S., 2012: Delayed phenology and reduced fitness associated with climate change in a wild hibernator. *Nature*, **489(7417)**, 554.

Langan, S.J., Johnston, L., Donaghy, M.J., Youngson, A.F., Hay, D.W., and Soulsby, C., 2001: Variation in river water temperatures in an upland stream over a 30-year period. *Science of the Total Environment*, **265(1-3)**, 195-207.

Langley, J.A., and Megonigal, J.P., 2010: Ecosystem response to elevated CO(2) levels limited by nitrogen-induced plant species shift. *Nature*, **466(7302)**, 96-99.

Lantz, T.C., Gergel, S.E., and Henry, G.H.R., 2010: Response of green alder (Alnus viridis subsp. fruticosa) patch dynamics and plant community composition to fire and regional temperature in north-western Canada. *Journal of Biogeography*, **37(8)**, 1597-1610.

Lantz, T.C., Kokelj, S.V., Gergel, S.E., and Henry, G.H.R., 2009: Relative impacts of disturbance and temperature: persistent changes in microenvironment and vegetation in retrogressive thaw slumps. *Global Change Biology,* **15(7)**, 1664-1675.

Lapola, D.M., Oyama, M.D., and Nobre, C.A., 2009: Exploring the range of climate biome projections for tropical South America: The role of CO2 fertilization and seasonality. *Global Biogeochem. Cycles,* **23(3)**, GB3003.

Lapola, D.M., Schaldach, R., Alcamo, J., Bondeau, A., Koch, J., Koelking, C., and Priess, J.A., 2010: Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceedings of the National Academy of Sciences of the United States of America,* **107(8)**, 3388-3393.

Larsen, K.S., Andresen, L.C., Beier, C., Jonasson, S., Albert, K.R., Ambus, P., Arndal, M.F., Carter, M.S., Christensen, S., Holmstrup, M., Ibrom, A., Kongstad, J., van der Linden, L., Maraldo, K., Michelsen, A., Mikkelsen, T.N., Pilegaard, K., Prieme, A., Ro-Poulsen, H., Schmidt, I.K., Selsted, M.B., and Stevnbak, K., 2011: Reduced N cycling in response to elevated CO2, warming, and drought in a Danish heathland: Synthesizing results of the CLIMAITE project after two years of treatments. *Global Change Biology,* **17(5)**, 1884-1899.

Laurance, W.F., Useche, D.C., Shoo, L.P., Herzog, S.K., Kessler, M., Escobar, F., Brehm, G., Axmacher, J.C., Chen, I.C., Gamez, L.A., Hietz, P., Fiedler, K., Pyrcz, T., Wolf, J., Merkord, C.L., Cardelus, C., Marshall, A.R., Ah-Peng, C., Aplet, G.H., Arizmendi, M.D., Baker, W.J., Barone, J., Bruhl, C.A., Bussmann, R.W., Cicuzza, D., Eilu, G., Favila, M.E., Hemp, A., Hemp, C., Homeier, J., Hurtado, J., Jankowski, J., Kattan, G., Kluge, J., Kromer, T., Lees, D.C., Lehnert, M., Longino, J.T., Lovett, J., Martin, P.H., Patterson, B.D., Pearson, R.G., Peh, K.S.H., Richardson, B., Richardson, M., Samways, M.J., Senbeta, F., Smith, T.B., Utteridge, T.M.A., Watkins, J.E., Wilson, R., Williams, S.E., and Thomas, C.D., 2011: Global warming, elevational ranges and the vulnerability of tropical biota. *Biological Conservation,* **144(1)**, 548-557.

Lavergne, S., Evans, M.E.K., Burfield, I.J., Jiguet, F., and Thuiller.W., 2013: Are species' responses to global change predicted by past niche evolution? *Philosophical Transactions of the Royal Society B: Biological Sciences,* **368(1610)**.

Lavergne, S., Mouquet, N., Thuiller, W., and Ronce, O., 2010: Biodiversity and Climate Change: Integrating Evolutionary and Ecological Responses of Species and Communities. *Annual Review of Ecology, Evolution, and Systematics, Vol 41,* **41**, 321-350.

Lawrence, D.M., and Swenson, S.C., 2011: Permafrost response to increasing Arctic shrub abundance depends on the relative influence of shrubs on local soil cooling versus large-scale climate warming. *Environmental Research Letters,* **6(4)**.

Lawrence, D.M., Thornton, P.E., Oleson, K.W., and Bonan, G.B., 2007: The Partitioning of Evpotranspiration into Transpiration, Soil Evaporation, and Canopy Evaporation in a GCM: Impacts on Land-Atmosphere Interaction. *Journal of Hydrometeorology,* **8**, 862-880.

Lawson, C.R., Bennie, J.J., Thomas, C.D., Hodgson, J.A., and Wilson, R.J., 2012: Local and landscape management of an expanding range margin under climate change. *Journal of Applied Ecology,* **49**, 552-561.

Le Conte, Y., and Navajas, M., 2008: Climate change: impact on honey bee populations and diseases. *Revue Scientifique Et Technique-Office International Des Epizooties,* **27(2)**, 499-510.

Le Quere, C., Raupach, M.R., Canadell, J.G., and Marland, G., 2009: Trends in the sources and sinks of carbon dioxide. *Nature Geoscience,* **2(12)**, 831-836.

Leadley, P., Periera, H.N., Alkemade, R., Fernandez-Manjarres, J.F., Proenca, V., Scharlemann, J.P.W., and Walpole, M.J., 2010: *Biodiversity Scenarios: Projections of 21st century change in biodiversity and associated ecosystem services.* Technical series Series 50, Montreal, 132 pp.

Leakey, A.D.B., Ainsworth, E.A., Bernacchi, C.J., Rogers, A., Long, S.P., and Ort, D.R., 2009: Elevated CO2 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *Journal of Experimental Botany,* **60(10)**, 2859-2876.

Leal, M., and Gunderson, A.R., 2012: Rapid Change in the Thermal Tolerance of a Tropical Lizard. *American Naturalist,* **180(6)**, 815-822.

Lee, M., Manning, P., Rist, J., Power, S.A., and Marsh, C., 2010: A global comparison of grassland biomass responses to CO2 and nitrogen enrichment. *Philosophical Transactions of the Royal Society B-Biological Sciences,* **365(1549)**, 2047-2056.

Leishman, M.R., Haslehurst, T., Ares, A., and Baruch, Z., 2007: Leaf trait relationships of native and invasive plants: community- and global-scale comparisons. *New Phytologist,* **176(3)**, 635-643.

Lenoir, J., Gegout, J.C., Dupouey, J.L., Bert, D., and Svenning, J.C., 2010: Forest plant community changes during 1989-2007 in response to climate warming in the Jura Mountains (France and Switzerland). *Journal of Vegetation Science*, **21(5)**, 949-964.

Lenoir, J., Gegout, J.C., Marquet, P.A., de Ruffray, P., and Brisse, H., 2008: A significant upward shift in plant species optimum elevation during the 20th century. *Science*, **320(5884)**, 1768-1771.

Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S., and Schellnhuber, H.J., 2008: Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences of the United States of America*, **105(6)**, 1786-1793.

Leonelli, G., Pelfini, M., Morra di Cella, U., and Garavaglia, V., 2011: Climate Warming and the Recent Treeline Shift in the European Alps: The Role of Geomorphological Factors in High-Altitude Sites. *AMBIO: A Journal of the Human Environment*, **40(3)**, 264-273.

Leuning, R., 1995: A critical appraisal of a combined stomatalphotosynthesis
model for C3 plants. *Plant, Cell and Environment*, **18**, 339-355.

Leuzinger, S., and Körner, C., 2010: Rainfall distribution is the main driver of runoff under future CO2-concentration in a temperate deciduous forest. *Global Change Biology*, **16(1)**, 246-254.

Leuzinger, S., Luo, Y.Q., Beier, C., Dieleman, W., Vicca, S., and Korner, C., 2011: Do global change experiments overestimate impacts on terrestrial ecosystems? *Trends in Ecology & Evolution*, **26(5)**, 236-241.

Levis, S., 2010: Modeling vegetation and land use in models of the Earth System. *Wiley Interdisciplinary Reviews: Climate Change*, **1(6)**, 840-856.

Lewis, S.L., Brando, P.M., Phillips, O.L., van der Heijden, G.M.F., and Nepstad, D., 2011: The 2010 Amazon Drought. *Science*, **331(6017)**, 554-554.

Lewis, S.L., Lloyd, J., Sitch, S., Mitchard, E.T.A., and Laurance, W.F., 2009a: Changing Ecology of Tropical Forests: Evidence and Drivers. *Annual Review of Ecology Evolution and Systematics*, **40**, 529-549.

Lewis, S.L., Lopez-Gonzalez, G., Sonke, B., Affum-Baffoe, K., Baker, T.R., Ojo, L.O., Phillips, O.L., Reitsma, J.M., White, L., Comiskey, J.A., Djuikouo, M.N., Ewango, C.E.N., Feldpausch, T.R., Hamilton, A.C., Gloor, M., Hart, T., Hladik, A., Lloyd, J., Lovett, J.C., Makana, J.R., Malhi, Y., Mbago, F.M., Ndangalasi, H.J., Peacock, J., Peh, K.S.H., Sheil, D., Sunderland, T., Swaine, M.D., Taplin, J., Taylor, D., Thomas, S.C., Votere, R., and Wöll, H., 2009b: Increasing carbon storage in intact African tropical forests. *Nature*, **457**, 1003-1007.

Li, D.Z., and Pritchard, H.W., 2009: The science and economics of ex situ plant conservation. *Trends in Plant Science*, **14(11)**, 614-621.

Li, W.H., Dickinson, R.E., Fu, R., Niu, G.Y., Yang, Z.L., and Canadell, J.G., 2007: Future precipitation changes and their implications for tropical peatlands. *Geophysical Research Letters*, **34(L01403)**, 1-6.

Li, Z., Liu, W.-z., Zhang, X.-c., and Zheng, F.-l., 2009: Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. *Journal of Hydrology*, **377(1–2)**, 35-42.

Liao, J.D., Boutton, T.W., and Jastrow, J.D., 2006: Storage and dynamics of carbon and nitrogen in soil physical fractions following woody plant invasion of grassland. *Soil Biology and Biochemistry*, **38(11)**, 3184-3196.

Liljedahl, A., Hinzman, L., Busey, R., and Yoshikawa, K., 2007: Physical short-term changes after a tussock tundra fire, Seward Peninsula, Alaska. *J. Geophys. Res.*, **112(F2)**, F02S07.

Lima, I.B.T., Ramos, F.M., Bambace, L.A.W., and Rosa, R.R., 2008: Methane Emissions from Large Dams as Renewable Energy Resources: A Developing Nation Perspective. . *Mitigation and Adaptation Strategies for Global Change*, **13**, 193-206.

Limpens, J., Berendse, F., Blodau, C., Canadell, J.G., Freeman, C., Holden, J., Roulet, N., Rydin, H., and Schaepman-Strub, G., 2008: Peatlands and the carbon cycle: from local processes to global implications - a synthesis. *Biogeosciences*, **5(5)**, 1475-1491.

Limpens, J., Granath, G., Gunnarsson, U., Aerts, R., Bayley, S., Bragazza, L., Bubier, J., Buttler, A., van den Berg, L.J.L., Francez, A.J., Gerdol, R., Grosvernier, P., Heijmans, M., Hoosbeek, M.R., Hotes, S., Ilomets, M., Leith, I., Mitchell, E.A.D., Moore, T., Nilsson, M.B., Nordbakken, J.F., Rochefort, L., Rydin, H., Sheppard, L.J., Thormann, M., Wiedermann, M.M., Williams, B.L., and Xu, B., 2011: Climatic modifiers of the response to nitrogen deposition in peat-forming Sphagnum mosses: a meta-analysis. *New Phytologist*, **191(2)**, 496-507.

Linares, J.C., Camarero, J.J., and Carreira, J.A., 2009: Interacting effects of changes in climate and forest cover on mortality and growth of the southernmost European fir forests. *Global Ecology and Biogeography*, **18(4)**, 485-497.

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolstrom, M., Lexer, M.J., and Marchetti, M., 2010: Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management*, **259(4)**, 698-709.

Lips, K.R., Diffendorfer, J., Mendelson, J.R., and Sears, M.W., 2008: Riding the wave: Reconciling the roles of disease and climate change in amphibian declines. *Plos Biology*, **6(3)**, 441-454.

Littell, J.S., McKenzie, D., Peterson, D.L., and Westerling, A.L., 2009: Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. . *Ecological Applications*, **19**, 1003-1021.

Littell, J.S., Oneil, E.E., McKenzie, D., Hicke, J.A., Lutz, J.A., Norheim, R.A., and Elsner, M.M., 2010: Forest ecosystems, disturbance, and climatic change in Washington State, USA. *Climatic Change*, **102(1-2)**, 129-158.

Liu, H., Allen, C., Guo, D., Williams, A.P., Wu, X., Anenkhonov, O.A., Liang, E., Sandanov, D.V., Badmaeva, N.K., and Yin., Y., in revision: Rapid growing season warming accelerates tree growth decline in semi-arid forests of Inner Asia. *Global Change Biology*.

Liu, W., Zhang, Z., and Wan, S., 2009: Predominant role of water in regulating soil and microbial respiration and their responses to climate change in a semiarid grassland. *Global Change Biology*, **15(1)**, 184-195.

Lloyd, A.H., Bunn, A.G., and Berner, L., 2011: A latitudinal gradient in tree growth response to climate warming in the Siberian taiga. *Global Change Biology*, **17(5)**, 1935-1945.

Lloyd, A.H., and Fastie, C.L., 2003: Recent changes in tree line forest distribution and structure in interior Alaska. *Ecoscience*, **10**, 176-185.

Lloyd, J., and Farquhar, G.D., 2008: Effects of rising temperatures and [CO2] on the physiology of tropical forest trees. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **363(1498)**, 1811-1817.

Loader, N.J., Walsh, R.P.D., Robertson, I., Bidin, K., Ong, R.C., Reynolds, G., McCarroll, D., Gagen, M., and Young, G.H.F., 2011: Recent trends in the intrinsic water-use efficiency of ringless rainforest trees in Borneo. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **366(1582)**, 3330-3339.

Loarie, S.R., Duffy, P.B., Hamilton, H., Asner, G.P., Field, C.B., and Ackerly, D.D., 2009: The velocity of climate change. *Nature*, **462(7276)**, 1052-U1111.

Loarie, S.R., Lobell, D.B., Asner, G.P., Mu, Q., and Field, C.B., 2011: Direct impacts on local climate of sugar-cane expansion in Brazil. *Nature Climate Change*, **1(2)**, 105-109.

Lobell, D.B., Schlenker, W., and Costa-Roberts, J., 2011: Climate Trends and Global Crop Production Since 1980. *Science*, **333(6042)**, 616-620.

Long, S.P., Ainsworth, E.A., Rogers, A., and Ort, D.R., 2004: Rising atmospheric carbon dioxied: plants FACE the future. *Annual Review of Plant Biology*, **55(1)**, 591-628.

Lorenzen, E.D., Nogues-Bravo, D., Orlando, L., Weinstock, J., Binladen, J., Marske, K.A., Ugan, A., Borregaard, M.K., Gilbert, M.T.P., Nielsen, R., Ho, S.Y.W., Goebel, T., Graf, K.E., Byers, D., Stenderup, J.T., Rasmussen, M., Campos, P.F., Leonard, J.A., Koepfli, K.P., Froese, D., Zazula, G., Stafford, T.W., Aaris-Sorensen, K., Batra, P., Haywood, A.M., Singarayer, J.S., Valdes, P.J., Boeskorov, G., Burns, J.A., Davydov, S.P., Haile, J., Jenkins, D.L., Kosintsev, P., Kuznetsova, T., Lai, X.L., Martin, L.D., McDonald, H.G., Mol, D., Meldgaard, M., Munch, K., Stephan, E., Sablin, M., Sommer, R.S., Sipko, T., Scott, E., Suchard, M.A., Tikhonov, A., Willerslev, R., Wayne, R.K., Cooper, A., Hofreiter, M., Sher, A., Shapiro, B., Rahbek, C., and Willerslev, E., 2011: Species-specific responses of Late Quaternary megafauna to climate and humans. *Nature*, **479(7373)**, 359-U195.

Loss, S.R., Terwilliger, L.A., and Peterson, A.C., 2011: Assisted colonization: Integrating conservation strategies in the face of climate change. *Biological Conservation*, **144(1)**, 92-100.

Lu, C.Q., Tian, H.Q., Liu, M.L., Ren, W., Xu, X.F., Chen, G.S., and Zhang, C., 2012: Effect of nitrogen deposition on China's terrestrial carbon uptake in the context of multifactor environmental changes. *Ecological Applications*, **22(1)**, 53-75.

Lu, J., Deser, C., and Reichler, T., 2009: Cause of the widening of the tropical belt since 1958. *Geophysical Research Letters*, **36**.

Luckman, B., and Kavanagh, T., 2000: Impact of Climate Fluctuations on Mountain Environments in the Canadian Rockies. *AMBIO: A Journal of the Human Environment*, **29(7)**, 371-380.

Lunt, I.D., Winsemius, L.M., McDonald, S.P., Morgan, J.W., and Dehaan, R.L., 2010: How widespread is woody plant encroachment in temperate Australia? Changes in woody vegetation cover in lowland woodland and coastal ecosystems in Victoria from 1989 to 2005. *Journal of Biogeography*, **37(4)**, 722-732.

Luo, Y., Wan, S., Hui, D., and Wallace, L., 2001: Acclimatization of soil respiration to warming in a tall grass prairie. *Nature*, **413(6856)**, 622-625.

Luo, Y.Q., Gerten, D., Le Maire, G., Parton, W.J., Weng, E.S., Zhou, X.H., Keough, C., Beier, C., Ciais, P., Cramer, W., Dukes, J.S., Emmett, B., Hanson, P.J., Knapp, A., Linder, S., Nepstad, D., and Rustad, L., 2008: Modeled interactive effects of precipitation, temperature, and [CO2] on ecosystem carbon and water dynamics in different climatic zones. *Global Change Biology*, **14(9)**, 1986-1999.

Luyssaert, S., Ciais, P., Piao, S.L., Schulze, E.D., Jung, M., Zaehle, S., Schelhaas, M.J., Reichstein, M., Churkina, G., Papale, D., Abril, G., Beer, C., Grace, J., Loustau, D., Matteucci, G., Marnani, F., Nabuurs, G.J., Verbeeck, H., Sulkava, M., Van Der Werf, G.R., Janssens, I.A., and Members of the Carboeurope, I.P.S.T., 2010: The European carbon balance. Part 3: forests. *Global Change Biology*, **16(5)**, 1429-1450.

Lydeard, C., Cowie, R.H., Ponder, W.F., Bogan, A.E., Bouchet, P., Clark, S.A., Cummings, K.S., Frest, T.J., Gargominy, O., Herbert, D.G., Hershler, R., Perez, K.E., Roth, B., Seddon, M., Strong, E.E., and Thompson, F.G., 2004: The global decline of nonmarine mollusks. *Bioscience*, **54(4)**, 321-330.

Ma, L.N., Lu, X.T., Liu, Y., Guo, J.X., Zhang, N.Y., Yang, J.Q., and Wang, R.Z., 2011: The Effects of Warming and Nitrogen Addition on Soil Nitrogen Cycling in a Temperate Grassland, Northeastern China. *PLoS One*, **6(11)**, 1-8.

Ma, T., and Zhou, C.G., 2012: Climate-associated changes in spring plant phenology in China. *International Journal of Biometeorology*, **56(2)**, 269-275.

Ma, Z., Peng, C., Zhu, Q., Chen, H., Yu, G., Li, W.H., Zhou, X., Wang, W., and Zhang, W., 2012: Regional drought-induced reduction in the biomass carbon sink of Canada's boreal forests. *Proceedings of the National Academy of Sciences*, **109(7)**, 2423-2427.

MacArthur, A.G., 1973: *Grassland fire danger meter Mk I (published as a circular slide rule).* Canberra,pp.

MacDonald, G.M., 2010: Global warming and the Arctic: a new world beyond the reach of the Grinnellian niche? *The Journal of Experimental Biology*, **213**, 855-861.

MacDonald, G.M., Bennett, K.D., Jackson, S.T., Parducci, L., Smith, F.A., Smol, J.P., and Willis, K.J., 2008: Impacts of climate change on species, populations and communities: palaeobiogeographical insights and frontiers. *Progress In Physical Geography*, **32(2)**, 139-172.

Macias Fauria, M., and Johnson, E.A., 2008: Climate and wildfires in the North American boreal forest. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, **363(1501)**, 2317-2329.

Mack, M.C., Bret-Harte, M.S., Hollingsworth, T.N., Jandt, R.R., Schuur, E.A.G., Shaver, G.R., and Verbyla, D.L., 2011: Carbon loss from an unprecedented Arctic tundra wildfire. *Nature*, **475(7357)**, 489-492.

Mack, M.C., Treseder, K.K., Manies, K.L., Harden, J.W., Schuur, E.A.G., Vogel, J.G., Randerson, J.T., and Chapin, F.S., 2008: Recovery of aboveground plant biomass and productivity after fire in mesic and dry black spruce forests of interior alaska. *Ecosystems*, **11(2)**, 209-225.

Mackelprang, R., Waldrop, M.P., DeAngelis, K.M., David, M.M., Chavarria, K.L., Blazewicz, S.J., Rubin, E.M., and Jansson, J.K., 2011: Metagenomic analysis of a permafrost microbial community reveals a rapid response to thaw. *Nature*, **480(7377)**, 368-U120.

Maclachlan, J.S., Hellmann, J.J., and Schwarz, M.W., 2007: A Framework for Debate of Assisted Migration in an Era of Climate Change. *Conservation Biology*, **21(2)**, 297-302.

Magalhães, M.F., Beja, P., Schlosser, I.J., and Collares-Pereira, M.J., 2007: Effects of multi-year droughts on fish assemblages of seasonally drying Mediterranean streams. *Freshwater Biology*, **52(8)**, 1494-1510.

Magnani, F., Mencuccini, M., Borghetti, M., Berbigier, P., Berninger, F., Delzon, S., Grelle, A., Hari, P., Jarvis, P.G., Kolari, P., Kowalski, A.S., Lankreijer, H., Law, B.E., Lindroth, A., Loustau, D., Manca, G., Moncrieff, J.B., Rayment, M., Tedeschi, V., Valentini, R., and Grace, J., 2007: The human footprint in the carbon cycle of temperate and boreal forests. *Nature*, **447(7146)**, 848-850.

Mainka, S.A., and Howard, G.W., 2010: Climate change and invasive species: double jeopardy. *Integrative Zoology*, **5(2)**, 102-111.

Malcolm, J.R., Liu, C.R., Neilson, R.P., Hansen, L., and Hannah, L., 2006: Global warming and extinctions of endemic species from biodiversity hotspots. *Conservation Biology*, **20(2)**, 538-548.

Malhi, Y., Aragao, L., Metcalfe, D.B., Paiva, R., Quesada, C.A., Almeida, S., Anderson, L., Brando, P., Chambers, J.Q., da Costa, A.C.L., Hutyra, L.R., Oliveira, P., Patino, S., Pyle, E.H., Robertson, A.L., and Teixeira, L.M., 2009a: Comprehensive assessment of carbon productivity, allocation and storage in three Amazonian forests. *Global Change Biology*, **15(5)**, 1255-1274.

Malhi, Y., Aragao, L.E.O.C., Galbraith, D., Huntingford, C., Fisher, R., Zelazowski, P., Sitch, S., McSweeney, C., and Meir, P., 2009b: Exploring the likelihood and mechanism of a climate-change-induced dieback of the

Amazon rainforest. *Proceedings of the National Academy of Sciences of the United States of America*, **106(49)**, 20610-20615.

Malmqvist, B., S.D., R., A.P., C., A.P., H., A.G., R., and C.R., T., 2007: Prospects for streams and rivers: An ecological perspective. In *Aquatic ecosystems: trends and global prospects.* [N. V. C. Polunin (ed.)]. Cambridge Press, Cambridge, UK, pp. 19-29.

Maniatis, D., Malhi, Y., Andre, L.S., Mollicone, D., Barbier, N., Saatchi, S., Henry, M., Tellier, L., Schwartzenberg, M., and White, M., 2011: Evaluating the Potential of Commercial Forest Inventory Data to Report on Forest Carbon Stock and Forest Carbon Stock Changes for REDD+under the UNFCCC. doi. *International Journal of Forestry Research,* **2011(134526)**, 2-14.

Mann, D.H., Rupp, T.S., Olson, M.A., and Duffy, P.A., 2012: Is Alaska's Boreal Forest Now Crossing a Major Ecological Threshold? *Arctic Antarctic and Alpine Research,* **44(3)**, 319-331.

Maraldo, K., Schmidt, I.K., Beier, C., and Holmstrup, M., 2008: Can field populations of the enchytraeid, Cognettia sphagnetorum, adapt to increased drought stress? *Soil Biology & Biochemistry,* **40(7)**, 1765-1771.

Marengo, J.A., Tomasella, J., Alves, L.M., Soares, W.R., and Rodriguez, D.A., 2011: The drought of 2010 in the context of historical droughts in the Amazon region. *Geophys. Res. Lett.,* **38(12)**, L12703.

Marini, L., Ayres, M., Battisti, A., and Faccoli, M., 2012: Climate affects severity and altitudinal distribution of outbreaks in an eruptive bark beetle. *Climatic Change,* **115(2)**, 327-341.

Marlon, J.R., Bartlein, P.J., Daniau, A.-L., Harrison, S.P., Maezumi, S.Y., Power, M.J., Tinner, W., and Vanniére, B., 2013: Global biomass burning: a synthesis and review of Holocene paleofire records and their controls. *Quaternary Science Reviews,* **65(0)**, 5-25.

Marlon, J.R., Bartlein, P.J., Walsh, M.K., Harrison, S.P., Brown, K.J., Edwards, M.E., Higuera, P.E., Power, M.J., Anderson, R.S., Briles, C., Brunelle, A., Carcaillet, C., Daniels, M., Hu, F.S., Lavoie, M., Long, C., Minckley, T., Richard, P.J.H., Scott, A.C., Shafer, D.S., Tinner, W., Umbanhowar, C.E., and Whitlock, C., 2009: Wildfire responses to abrupt climate change in North America. *Proceedings of the National Academy of Sciences of the United States of America,* **106(8)**, 2519-2524.

Martin, D., Lal, T., Sachdev, C.B., and Sharma, J.P., 2010: Soil organic carbon storage changes with climate change, landform and land use conditions in Garhwal hills of the Indian Himalayan mountains. *Agriculture, Ecosystems & Environment,* **138(1–2)**, 64-73.

Martin, T.E., and Maron, J.L., 2012: Climate impacts on bird and plant communities from altered animal-plant interactions. *Nature Climate Change,* **2(3)**, 195-200.

Martinez-Alier, J., 2011: The EROI of Agriculture and its use by the Via Campesina. *The Journal of Peasant Studies,* **38(1)**, 145-160.

Martinez, P.J., 2012: Invasive crayfish in a high desert river: Implications of concurrent invaders and climate change. *Aquatic Invasions,* **7(2)**, 219-234.

Maseyk, K., Hemming, D., Angert, A., Leavitt, S.W., and Yakir, D., 2011: Increase in water-use efficiency and underlying processes in pine forests across a precipitation gradient in the dry Mediterranean region over the past 30 years. *Oecologia,* **167(2)**, 573-585.

Maslin, M., Owen, M., Betts, R., Day, S., Dunkley Jones, T., and Ridgwell, A., 2010: Gas hydrates: past and future geohazard? *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences,* **368(1919)**, 2369-2393.

Mastrandrea, M.D., Field, C.B., Stocker, T.F., Edenhofer, O., Ebi, K.L., Frame, D.J., Held, H., Kriegler, E., Mach, K.J., Matschoss, P.R., Plattner, G.-K., Yohe, G.W., and Zwiers, F.W., 2010: *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. Intergovernmental Panel on Climate Change (IPCC).* Available at <**Fehler! Hyperlink-Referenz ungültig.**, 5 pp.

Matthews, S.N., Iverson, L.R., Prasad, A.M., Peters, M.P., and Rodewald, P.G., 2011: Modifying climate change habitat models using tree species-specific assessments of model uncertainty and life history-factors. *Forest Ecology and Management,* **262(8)**, 1460-1472.

Matthiessen, B., Mielke, E., and Sommer, U., 2010: Dispersal decreases diversity in heterogeneous metacommunities by enhancing regional competition. *Ecology,* **91(7)**, 2022-2033.

Mattila, N., Kaitala, V., Komonen, A., Paivinen, J., and Kotiaho, J.S., 2011: Ecological correlates of distribution change and range shift in butterflies. *Insect Conservation and Diversity,* **4(4)**, 239-246.

Matusick, G., Ruthrof, K.X., Brouwers, N.C., Dell, B., and Hardy, G.S.J., 2013: Sudden forest canopy collapse corresponding with extreme drought and heat in a mediterranean-type eucalypt forest in southwestern Australia. 1-14.

Matusick, G., Ruthrof, K.X., and Hardy, G.S.J., 2012: Drought and Heat Triggers Sudden and Severe Dieback in a Dominant Mediterranean-Type Woodland Species. *Open Journal of Forestry,* **2(4)**, 183-186.

Matzek, V., 2012: Trait Values, Not Trait Plasticity, Best Explain Invasive Species' Performance in a Changing Environment. *PLoS One,* **7(10)**.

Mayle, F.E., and Power, M.J., 2008: Impact of a drier Early-Mid-Holocene climate upon Amazonian forests. *Philosophical Transactions of the Royal Society B-Biological Sciences,* **363(1498)**, 1829-1838.

McAfee, K., 2012: The contradictory logic of global ecosystem services markets. *Development and Change,* **43(1)**, 105-131.

McAlpine, C.A., Syktus, J., Ryan, J.G., Deo, R.C., Mckeon, G.M., Mcgowan, H.A., and Phinn, S.R., 2009: A continent under stress: interactions, feedbacks and risks associated with impact of modified land cover on Australia's climate. *Global Change Biology,* **15(9)**, 2206-2223.

McCain, C.M., and Colwell, R.K., 2011: Assessing the threat to montane biodiversity from discordant shifts in temperature and precipitation in a changing climate. *Ecology Letters,* **14(12)**, 1236-1245.

McCarthy, H.R., Oren, R., Johnsen, K.H., Gallet-Budynek, A., Pritchard, S.G., Cook, C.W., LaDeau, S.L., Jackson, R.B., and Finzi, A.C., 2010: Re-assessment of plant carbon dynamics at the Duke free-air CO2 enrichment site: interactions of atmospheric [CO2] with nitrogen and water availability over stand development. *New Phytologist,* **185(2)**, 514-528.

McDougall, K.L., Alexander, J.M., Haider, S., Pauchard, A., Walsh, N.G., and Kueffer, C., 2011: Alien flora of mountains: global comparisons for the development of local preventive measures against plant invasions. *Diversity and Distributions,* **17(1)**, 103-111.

McDowell, N.G., Beerling, D.J., Breshears, D.D., Fisher, R.A., Raffa, K.F., and Stitt, M., 2011: The interdependence of mechanisms underlying climate-driven vegetation mortality. *Trends in Ecology & Evolution,* **26(10)**, 523-532.

McGeoch, M.A., Butchart, S.H.M., Spear, D., Marais, E., Kleynhans, E.J., Symes, A., Chanson, J., and Hoffmann, M., 2010: Global indicators of biological invasion: species numbers, biodiversity impact and policy responses. *Diversity and Distributions,* **16(1)**, 95–108.

McGuire, A.D., Chapin, F.S., Wirth, C., Apps, M., Bhatti, J., Callaghan, T., Christensen, T.R., Clein, J.S., Fukuda, M., Maximov, T., Onuchin, A., Shvidenko, A., Vaganov, E., Canadell, J.G., Pataki, D.E., and Pitelka, L.F., 2007: Responses of high latitude ecosystems to global change: potential consequences for the climate system. In *Terrestrial Ecosystems in a Changing World*. Springer Berlin Heidelberg, pp. 297-310.

McGuire, A.D., Christensen, T.R., Hayes, D., Heroult, A., Euskirchen, E., Yi, Y., Kimball, J.S., Koven, C., Lafleur, P., Miller, P.A., Oechel, W., Peylin, P., and Williams, M., 2012: An assessment of the carbon balance of arctic tundra: comparisons among observations, process models, and atmospheric inversions. *Biogeosciences Discuss.,* **9(4)**, 4543-4594.

McGuire, A.D., Hayes, D.J., Kicklighter, D.W., Manizza, M., Zhuang, Q., Chen, M., Follows, M.J., Gurney, K.R., McClelland, J.W., Melillo, J.M., Peterson, B.J., and Prinn, R.G., 2010: An analysis of the carbon balance of the Arctic Basin from 1997 to 2006. *Tellus Series B-Chemical and Physical Meteorology,* **62(5)**, 455-474.

McKenzie, V.J., and Peterson, A.C., 2012: Pathogen pollution and the emergence of a deadly amphibian pathogen. *Molecular Ecology,* **21(21)**, 5151-5154.

McKinney, M., 2008: Effects of urbanization on species richness: A review of plants and animals. *Urban Ecosystems,* **11(2)**, 161-176.

McLachlan, J.S., Clark, J.S., and Manos, P.S., 2005: Molecular indicators of tree migration capacity under rapid climate change. *Ecology,* **86(8)**, 2088-2098.

McLaughlin, S.B., Nosal, M., Wullschleger, S.D., and Sun, G., 2007: Interactive effects of ozone and climate on tree growth and water use in a southern Appalachian forest in the USA. *New Phytologist,* **174(1)**, 109-124.

McMahon, S.M., Harrison, S.P., Armbruster, W.S., Bartlein, P.J., Beale, C.M., Edwards, M.E., Kattge, J., Midgley, G., Morin, X., and Prentice, I.C., 2011: Improving assessment and modelling of climate change impacts on global terrestrial biodiversity. *Trends in Ecology & Evolution,* **26(5)**, 249-259.

McMenamin, S.K., and Hannah, L., 2012: First Extinctions on Land. In *Saving a Million Species: Extinction Risk from Climate Change* [L. Hannah (ed.)]. Island Press, Washington Covelo London, pp. 89-102.

McMurtrie, R.E., Iversen, C.M., Dewar, R.C., Medlyn, B.E., Nasholm, T., Pepper, D.A., and Norby, R.J., 2012: Plant root distributions and nitrogen uptake predicted by a hypothesis of optimal root foraging. *Ecology and Evolution,* **2(6)**, 1235-1250.

McPherson, R.A., 2007: A review of vegetation-atmosphere interactions and their influences on mesoscale phenomena. *Progress in Physical Geography*, **31(3)**, 261-285.

Mehl, J.W., Geldenhuys, C.J., Roux, J., and Wingfield, M.J., 2010: Die-back of kiaat (Pterocarpus angolensis) in southern Africa: a cause for concern? *Southern Forests: a Journal of Forest Science*, **72(3-4)**, 121-132.

Meier, E.S., Lischke, H., Schmatz, D.R., and Zimmermann, N.E., 2012: Climate, competition and connectivity affect future migration and ranges of European trees. *Global Ecology and Biogeography*, **21(2)**, 164-178.

Mendelsohn, R., and Dinar, A., 2009: Land Use and Climate Change Interactions. *Annual Review of Resource Economics*, **1**, 309-332.

Menéndez, R., Gonzalez-Megias, A., Lewis, O.T., Shaw, M.R., and Thomas, C.D., 2008: Escape from natural enemies during climate-driven range expansion: a case study. *Ecological Entomology*, **33(3)**, 413-421.

Menge, D.N.L., and Field, C.B., 2007: Simulated global changes alter phosphorus demand in annual grassland. *Global Change Biology*, **13(12)**, 2582-2591.

Menzel, A., Jakobi, G., Ahas, R., Scheifinger, H., and Estrella, N., 2003: Variations of the climatological growing season (1951-2000) in Germany compared with other countries. *International Journal of Climatology*, **23(7)**, 793-812.

Menzel, A., Sparks, T.H., Estrella, N., Koch, E., Aasa, A., Ahas, R., Alm-Kubler, K., Bissolli, P., Braslavska, O., Briede, A., Chmielewski, F.M., Crepinsek, Z., Curnel, Y., Dahl, A., Defila, C., Donnelly, A., Filella, Y., Jatcza, K., Mage, F., Mestre, A., Nordli, O., Penuelas, J., Pirinen, P., Remisova, V., Scheifinger, H., Striz, M., Susnik, A., Van Vliet, A.J.H., Wielgolaski, F.E., Zach, S., and Zust, A., 2006: European phenological response to climate change matches the warming pattern. *Global Change Biology*, **12(10)**, 1969-1976.

Mercado, L.M., Bellouin, N., Sitch, S., Boucher, O., Huntingford, C., Wild, M., and Cox, P.M., 2009: Impact of changes in diffuse radiation on the global land carbon sink. *Nature*, **458(7241)**, 1014-U1087.

Merilä, J., 2012: Evolution in response to climate change: In pursuit of the missing evidence. *Bioessays*, **34(9)**, 811-818.

Meyers, E.M., Dobrowski, B., and Tague, C.L., 2010: Climate Change Impacts on Flood Frequency, Intensity, and Timing May Affect Trout Species in Sagehen Creek, California. *Transactions of the American Fisheries Society*, **139(6)**, 1657-1664.

Meyfroidt, P., and Lambin, E.F., 2011: Global Forest Transition: Prospects for an End to Deforestation. In *Annual Review of Environment and Resources, Vol 36* [A. Gadgil & D. M. Liverman (eds.)]. Annual Reviews, Palo Alto, pp. 343-371.

Midgley, G.F., Davies, I.D., Albert, C.H., Altwegg, R., Hannah, L., Hughes, G.O., O'Halloran, L.R., Seo, C., Thorne, J.H., and Thuiller, W., 2010: BioMove - an integrated platform simulating the dynamic response of species to environmental change. *Ecography*, **33(3)**, 612-616.

Mihoub, J.B., Mouawad, N.G., Pilard, P., Jiguet, F., Low, M., and Teplitsky, C., 2012: Impact of temperature on the breeding performance and selection patterns in lesser kestrels Falco naumanni. *Journal of Avian Biology*, **43(5)**, 472-480.

Miles, L., Newton, A.C., DeFries, R.S., Ravilious, C., May, I., Blyth, S., Kapos, V., and Gordon, J.E., 2006: A global overview of the conservation status of tropical dry forests. *Journal of Biogeography*, **33(3)**, 491-505.

Millar, C., Westfall, R., Delany, D., King, J., and Graumlich, L., 2004: Response of Subalpine Conifers in the Sierra Nevada, California, U.S.A., to 20th-century Warming and Decadal Climate Variability. *Arctic, Antarctic, and Alpine Research*, **36(2)**, 181-200.

Millar, C.I., Westfall, R.D., Delany, D.L., Bokach, M.J., Flint, A.L., and Flint, L.E., 2012: Forest mortality in high-elevation whitebark pine (Pinus albicaulis) forests of eastern California, USA; influence of environmental context, bark beetles, climatic water deficit, and warming. *Canadian Journal of Forest Research*, **42(4)**, 749-765.

Millennium Ecosystem Assessment, 2003: *Ecosystems and Human Wellbeing: A framework for Assessment*. Island Press, Washington DCpp.

Millennium Ecosystem Assessment, 2005a: *Ecosystems and Human wellbeing: Biodiversity synthesis*. World Resources Institute, Washington, DC, 86 pp.

Millennium Ecosystem Assessment, 2005b: *Ecosystems and human wellbeing: Desertification synthesis*. World Resources Institute, Washington DCpp.

Miller-Rushing, A.J., Lloyd-Evans, T.L., Primack, R.B., and Satzinger, P., 2008: Bird migration times, climate change, and changing population sizes. *Global Change Biology*, **14(9)**, 1959-1972.

Mills, G., Hayes, F., Simpson, D., Emberson, L., Norris, D., Harmens, H., and Buker, P., 2011: Evidence of widespread effects of ozone on crops and (semi-)natural vegetation in Europe (1990-2006) in relation to AOT40-and flux-based risk maps. *Global Change Biology,* **17(1)**, 592-613.

Mills, G., Hayes, F., Wilkinson, S., and Davies, W.J., 2009: Chronic exposure to increasing background ozone impairs stomatal functioning in grassland species. *Global Change Biology,* **15(6)**, 1522-1533.

Minteer, B.A., and Collins, J.P., 2010: Move it or lose it? The ecological ethics of relocating species under climate change. *Ecological Applications,* **20(7)**, 1801-1804.

Miranda, J.D., Padilla, F.M., and Pugnaire, F.I., 2009: Response of a Mediterranean semiarid community to changing patterns of water supply. *Perspectives in Plant Ecology Evolution and Systematics,* **11(4)**, 255-266.

Mishra, V., Cherkauer, K.A., Niyogi, D., Lei, M., Pijanowski, B.C., Ray, D.K., Bowling, L.C., and Yang, G., 2010: A regional scale assessment of land use/land cover and climatic changes on water and energy cycle in the upper Midwest United States. *International Journal of Climatology,* **30(13)**, 2025-2044.

Mitas, C.M., and Clement, A., 2005: Has the Hadley cell been strengthening in recent decades? *Geophysical Research Letters,* **32(3)**.

Mitchard, E.T.A., Saatchi, S.S., Gerard, F.F., Lewis, S.L., and Meir, P., 2009: Measuring woody encroachment along a forest-savanna boundary in Central Africa. *Earth Interactions,* **13(8)**, 1-29.

Mitchell, T.D., and Jones, P.D., 2005: An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology,* **25(6)**, 693-712.

Miyake, S., Renouf, M., Peterson, A., McAlpine, C., and Smith, C., 2012: Land-use and environmental pressures resulting from current and future bioenergy crop expansion: A review. *Journal of Rural Studies,* **28(4)**, 650-658.

Moiseyev, A., Solberg, B., Kallio, A.M.I., and Lindner, M., 2011: An economic analysis of the potential contribution of forest biomass to the EU RES target and its implications for the EU forest industries. *Journal of Forest Economics,* **17(2)**, 197-213.

Moleele, N.M., Ringrose, S., Matheson, W., and Vanderpost, C., 2002: More woody plants? The status of bush encroachment in Botswana’s grazing areas. *Journal of Environmental Management,* **64(1)**, 3-11.

Møller, A.P., Rubolini, D., and Lehikoinen, E., 2008: Populations of migratory bird species that did not show a phenological response to climate change are declining. *Proceedings of the National Academy of Sciences of the United States of America,* **105(42)**, 16195-16200.

Monahan, W.B., and Tingley, M.W., 2012: Niche Tracking and Rapid Establishment of Distributional Equilibrium in the House Sparrow Show Potential Responsiveness of Species to Climate Change. *PLoS One,* **7(7)**.

Monteith, J.L., 1965: Evaporation and environment. *Symp. Soc. Exp. Biol.,,* **19**, 205-224.

Montoya, J.M., and Raffaelli, D., 2010: The effects of climate change on biotic interactions and ecosystem services. *Philosophical Transactions of the Royal Society B-Biological Sciences,* **365(1549)**, 2011-2011.

Mooney, H.A., Bullock, S.H., and Medina, E., 1995: Introduction. In *Seasonally dry tropical forests* [S. H. Bullock, H. A. Mooney & E. Medina (eds.)]. Cambridge University Press, Cambridge, UK, pp. 1-8.

Morecroft, M.D., Crick, H.Q.P., Duffield, S.J., and Macgregor, N.A., 2012: Resilience to climate change: translating principles into practice. *Journal of Applied Ecology,* **49(3)**, 547-551.

Morin, X., Augspurger, C., and Chuine, I., 2007: Process-based modeling of species' distributions: What limits temperate tree species' range boundaries? *Ecology,* **88(9)**, 2280-2291.

Morin, X., and Thuiller, W., 2009: Comparing niche- and process-based models to reduce prediction uncertainty in species range shifts under climate change. *Ecology,* **90(5)**, 1301-1313.

Moritz, M.A., Parisien, M.A., Batllori, E., Krawchuk, M.A., Van Dorn, J., Ganz, D.J., and Hayhoe, K., 2012: Climate change and disruptions to global fire activity. *Ecosphere,* **3(49)**.

Morrison, J., Quick, M.C., and Foreman, M.G.G., 2002: Climate change in the Fraser River watershed: flow and temperature projections. *Journal of Hydrology,* **263(1-4)**, 230-244.

Mueller, A.D., Islebe, G.A., Hillesheim, M.B., Grzesik, D.A., Anselmetti, F.S., Ariztegui, D., Brenner, M., Curtis, J.H., Hodell, D.A., and Venz, K.A., 2009a: Climate drying and associated forest decline in the lowlands of northern Guatemala during the late Holocene. *Quaternary Research,* **71(2)**, 133-141.

Mueller, D.R., Van Hove, P., Antoniades, D., Jeffries, M.O., and Vincent, W.F., 2009b: High Arctic lakes as sentinel ecosystems: Cascading regime shifts in climate, ice cover, and mixing. *Limnology and Oceanography,* **54(6)**, 2371-2385.

Mueller, R.C., Scudder, C.M., Porter, M.E., Trotter, R.T., Gehring, C.A., and Whitham, T.G., 2005: Differential tree mortality in response to severe drought: evidence for long-term vegetation shifts. *Journal of Ecology,* **93(6)**, 1085-1093.

Muhlfeld, C.C., Giersch, J.J., Hauer, F.R., Pederson, G.T., Luikart, G., Peterson, D.P., Downs, C.C., and Fagre, D.B., 2011: Climate change links fate of glaciers and an endemic alpine invertebrate. *Climatic Change*, **106(2)**, 337-345.

Murdiyarso, D., Hergoualc'h, K., and Verchot, L.V., 2010: Opportunities for reducing greenhouse gas emissions in tropical peatlands. *Proceedings of the National Academy of Sciences of the United States of America*, **107(46)**, 19655-19660.

Musolin, D.L., Tougou, D., and Fujisaki, K., 2010: Too hot to handle? Phenological and life-history responses to simulated climate change of the southern green stink bug Nezara viridula (Heteroptera: Pentatomidae). *Global Change Biology*, **16(1)**, 73-87.

Myers-Smith, I.H., Forbes, B.C., Wilmking, M., Hallinger, M., Lantz, T., Blok, D., Tape, K.D., Macias-Fauria, M., Sass-Klaassen, U., Levesque, E., Boudreau, S., Ropars, P., Hermanutz, L., Trant, A., Collier, L.S., Weijers, S., Rozema, J., Rayback, S.A., Schmidt, N.M., Schaepman-Strub, G., Wipf, S., Rixen, C., Menard, C.B., Venn, S., Goetz, S., Andreu-Hayles, L., Elmendorf, S., Ravolainen, V., Welker, J., Grogan, P., Epstein, H.E., and Hik, D.S., 2011: Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities. *Environmental Research Letters*, **6(4)**, 1-15.

Nabuurs, G.J., Hengeveld, G.M., van der Werf, D.C., and Heidema, A.H., 2010: European forest carbon balance assessed with inventory based methods—An introduction to a special section. *Forest Ecology and Management*, **260(3)**, 239-240.

Naef-Daenzer, B., Luterbacher, J., Nuber, M., Rutishauser, T., and Winkel, W., 2012: Cascading climate effects and related ecological consequences during past centuries. *Climate of the Past*, **8(5)**, 1527-1540.

Naito, A.T., and Cairns, D.M., 2011: Patterns and processes of global shrub expansion. *Progress in Physical Geography*, **35(4)**, 423-442.

Nakazawa, T., and Doi, H., 2012: A perspective on match/mismatch of phenology in community contexts. *Oikos*, **121(4)**, 489-495.

Nathan, R., 2006: Long-distance dispersal of plants. *Science*, **313(5788)**, 786-788.

Nathan, R., Horvitz, N., He, Y.P., Kuparinen, A., Schurr, F.M., and Katul, G.G., 2011: Spread of North American wind-dispersed trees in future environments. *Ecology Letters*, **14(3)**, 211-219.

Nemet, G.F., 2009: Net Radiative Forcing from Widespread Deployment of Photovoltaics. *Environmental Science and Technology*, **43(6)**, 2173-2178.

Nepstad, D.C., Boyd, W., Stickler, C.M., Azevedo, A., and Bezerra, T., in press: Responding to Climate Change and the Global Land Crisis: REDD+, Market Transformation, and Low Emissions Rural Development. *Philosophical Transactions of the Royal Society - B*.

Nepstad, D.C., Stickler, C.M., Soares, B., and Merry, F., 2008: Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **363(1498)**, 1737-1746.

Nepstad, D.C., Tohver, I.M., Ray, D., Moutinho, P., and Cardinot, G., 2007: Mortality of large trees and lianas following experimental drought in an amazon forest. *Ecology*, **88(9)**, 2259-2269.

Ni, J., 2011: Impacts of climate change on Chinese ecosystems: key vulnerable regions and potential thresholds. *Regional Environmental Change*, **11**, S49-S64.

Niboyet, A., Brown, J.R., Dijkstra, P., Blankinship, J.C., Leadley, P.W., Le Roux, X., Barthes, L., Barnard, R.L., Field, C.B., and Hungate, B.A., 2011: Global Change Could Amplify Fire Effects on Soil Greenhouse Gas Emissions. *PLoS One*, **6(6)**, 1-10.

Nicholls, R.J., 2004: Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios. *Global Environmental Change-Human and Policy Dimensions*, **14(1)**, 69-86.

Nilsson, C., Reidy, C.A., Dynesius, M., and Revenga, C., 2005: Fragmentation and flow regulation of the world's large river systems. *Science*, **308(5720)**, 405-408.

Noble, I.R., Gill, A.M., and Bary, G.A.V., 1980: McArthur's fire-danger meters expressed as equations. *Australian Journal of Ecology*, **5(2)**, 201-203.

Nock, C.A., Baker, P.J., Wanek, W., Leis, A., Grabner, M., Bunyavejchewin, S., and Hietz, P., 2011: Long-term increases in intrinsic water-use efficiency do not lead to increased stem growth in a tropical monsoon forest in western Thailand. *Global Change Biology*, **17(2)**, 1049-1063.

Nogues-Bravo, D., Ohlemuller, R., Batra, P., and Araujo, M.B., 2010: Climate Predictors of Late Quaternary Extinctions. *Evolution*, **64(8)**, 2442-2449.

Norberg, J., Urban, M.C., Vellend, M., Klausmeier, C.A., and Loeuille, N., 2012: Eco-evolutionary responses of biodiversity to climate change. *Nature Climate Change*, **2(10)**, 747-751.

Norby, R.J., Warren, J.M., Iversen, C.M., Medlyn, B.E., and McMurtrie, R.E., 2010: CO2 enhancement of forest productivity constrained by limited nitrogen availability. *Proceedings of the National Academy of Sciences,* **107(45)**, 19368-19373.

Norby, R.J., and Zak, D.R., 2011: Ecological Lessons from Free-Air CO2 Enrichment (FACE) Experiments. In *Annual Review of Ecology, Evolution, and Systematics, Vol 42* [D. J. Futuyma, H. B. Shaffer & D. Simberloff (eds.)]. Annual Reviews, Palo Alto, pp. 181-203.

Normand, S., Treier, U.A., Randin, C., Vittoz, P., Guisan, A., and Svenning, J.C., 2009: Importance of abiotic stress as a range-limit determinant for European plants: insights from species responses to climatic gradients. *Global Ecology and Biogeography*, **18(4)**, 437-449.

Nowicki, P., Pepkowska, A., Kudlek, J., Skorka, P., Witek, M., Settele, J., and Woyciechowski, M., 2007: From metapopulation theory to conservation recommendations: Lessons from spatial occurrence and abundance patterns of Maculinea butterflies. *Biological Conservation,* **140(1-2)**, 119-129.

O'Connor, F.M., Boucher, O., Gedney, N., Jones, C.D., Folberth, G.A., Coppell, R., Friedlingstein, P., Collins, W.J., Chappellaz, J., Ridley, J., and Johnson, C.E., 2010: Possible role of wetlands, permafrost, and methane hydrates in the methane cycle under future climate change: a review. *Reviews of Geophysics,* **48(RG4005)**, 1-33.

O'Donnell, J.A., Harden, J.W., McGuire, A.D., Kanevskiy, M.Z., Jorgenson, M.T., and Xu, X.M., 2011: The effect of fire and permafrost interactions on soil carbon accumulation in an upland black spruce ecosystem of interior Alaska: implications for post-thaw carbon loss. *Global Change Biology,* **17(3)**, 1461-1474.

O'Halloran, T.L., Law, B.E., Goulden, M.L., Wang, Z., Barr, J.G., Schaaf, C., Brown, M., Fuentes, J.D., Göckede, M., Black, A., and Engel, V., 2012: Radiative forcing of natural forest disturbances. *Global Change Biology,* **18(2)**, 555-565.

O'Reilly, C.M., Alin, S.R., Plisnier, P.D., Cohen, A.S., and McKee, B.A., 2003: Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa. *Nature,* **424(6950)**, 766-768.

OECD/FAO, 2010: *OECD-FAO Agricultural Outlook 2010-2019.* 248 pp.

Ogawa-Onishi, Y., Berry, P.M., and Tanaka, N., 2010: Assessing the potential impacts of climate change and their conservation implications in Japan: A case study of conifers. *Biological Conservation,* **143(7)**, 1728-1736.

Oleszczuk, R., Regina, K., Szajdak, L., Höper, H., and Maryganova, V., 2008: Impacts of agricultural utilization of peat soils on the greenhouse gas balance. In *Peatlands and climate change* [M. Strack (ed.)]. International Peat Society, Finland, pp. 70-97.

Oliver, T., Hill, J.K., Thomas, C.D., Brereton, T., and Roy, D.B., 2009: Changes in habitat specificity of species at their climatic range boundaries. *Ecology Letters*, **12(10)**, 1091-1102.

Oliver, T.H., Gillings, S., Girardello, M., Rapacciuolo, G., Brereton, T.M., Siriwardena, G.M., Roy, D.B., Pywell, R., and Fuller, R.J., 2012: Population density but not stability can be predicted from species distribution models. *Journal of Applied Ecology,* **49(3)**, 581-590.

Oltmans, S.J., Lefohn, A.S., Harris, J.M., Tarasick, D.W., Thompson, A.M., Wernli, H., Johnson, B.J., Novelli, P.C., Montzka, S.A., Ray, J.D., Patrick, L.C., Sweeney, C., Jefferson, A., Dann, T., and Davies, J., 2006: Long term changes in tropospheric ozone. *Atmospheric Environment,* **40(17)**, 3156-3173.

Ormerod, S.J., 2009: Climate change, river conservation and the adaptation challenge. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **19(6)**, 609-613.

Osawa, A., Zyryanova, O.A., Matsuura, Y., Kajimoto, T., and Wein, R.W., 2010: *Permafrost Ecosystems: Siberian Larch Forests*. Springer, New York, 502 pp.

Ozgul, A., Childs, D.Z., Oli, M.K., Armitage, K.B., Blumstein, D.T., Olson, L.E., Tuljapurkar, S., and Coulson, T., 2010: Coupled dynamics of body mass and population growth in response to environmental change. *Nature,* **466(7305)**, 482-U485.

Paerl, H.W., Hall, N.S., and Calandrino, E.S., 2011: Controlling harmful cyanobacterial blooms in a world experiencing anthropogenic and climatic-induced change. *Science of the Total Environment,* **409(10)**, 1739-1745.

Paerl, H.W., and Paul, V.J., 2012: Climate change: links to global expansion of harmful cyanobacteria. *Water Res,* **46(5)**, 1349-1363.

Page, S.E., Rieley, J.O., and Banks, C.J., 2011: Global and regional importance of the tropical peatland carbon pool. *Global Change Biology,* **17(2)**, 798-818.

Page, S.E., Siegert, F., Rieley, J.O., Boehm, H.D., Jaya, A., and Limin, S., 2002: The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*, **420(6911)**, 61-65.

Palmer, M.A., and Filoso, S., 2009: Restoration of Ecosystem Services for Environmental Markets. *Science,* **325(5940)**, 575-576.

Pan, Y., Birdsey, R., Fang, J., Houghton, R., Kauppi, P., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., and Hayes, D., 2011: A Large and Persistent Carbon Sink in the World's Forests. *Science,* **333(6045)**, 988-993.

Pan, Y.D., Birdsey, R., Hom, J., and McCullough, K., 2009: Separating effects of changes in atmospheric composition, climate and land-use on carbon sequestration of US Mid-Atlantic temperate forests. *Forest Ecology and Management,* **259(2)**, 151-164.

Parent, M.B., and Verbyla, D., 2010: The Browning of Alaska's Boreal Forest. *Remote Sensing,* **2(12)**, 2729-2747.

Park Williams, A., Allen, C.D., Macalady, A.K., Griffin, D., Woodhouse, C.A., Meko, D.M., Swetnam, T.W., Rauscher, S.A., Seager, R., Grissino-Mayer, H.D., Dean, J.S., Cook, E.R., Gangodagamage, C., Cai, M., and McDowell, N.G., 2012: Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change,* **advance online publication**.

Parker-Allie, F., Musil, C.F., and Thuiller, W., 2009: Effects of climate warming on the distributions of invasive Eurasian annual grasses: a South African perspective. *Climatic Change,* **94(1-2)**, 87-103.

Parker, B.R., Vinebrooke, R.D., and Schindler, D.W., 2008: Recent climate extremes alter alpine lake ecosystems. *Proceedings of the National Academy of Sciences of the United States of America,* **105(35)**, 12927-12931.

Parmesan, C., 2006: Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology Evolution and Systematics,* **37**, 637-669.

Parmesan, C., 2007: Influences of species, latitudes and methodologies on estimates of phenological response to global warming. *Global Change Biology,* **13(9)**, 1860-1872.

Parmesan, C., and Yohe, G., 2003: A globally coherent fingerprint of climate change impacts across natural systems. *Nature,* **421(6918)**, 37-42.

Pateman, R.M., Hill, J.K., Roy, D.B., Fox, R., and Thomas, C.D., 2012: Temperature-Dependent Alterations in Host Use Drive Rapid Range Expansion in a Butterfly. *Science,* **336(6084)**, 1028-1030.

Pauli, H., Gottfried, M., Dullinger, S., Abdaladze, O., Akhalkatsi, M., Alonso, J.L.B., Coldea, G., Dick, J., Erschbamer, B., Calzado, R.F., Ghosn, D., Holten, J.I., Kanka, R., Kazakis, G., Kollar, J., Larsson, P., Moiseev, P., Moiseev, D., Molau, U., Mesa, J.M., Nagy, L., Pelino, G., Puscas, M., Rossi, G., Stanisci, A., Syverhuset, A.O., Theurillat, J.P., Tomaselli, M., Unterluggauer, P., Villar, L., Vittoz, P., and Grabherr, G., 2012: Recent Plant Diversity Changes on Europe's Mountain Summits. *Science,* **336(6079)**, 353-355.

Pauli, H., Gottfried, M., Reiter, K., Klettner, C., and Grabherr, G., 2007: Signals of range expansions and contractions of vascular plants in the high Alps: observations (1994-2004) at the GLORIA master site Schrankogel, Tyrol, Austria. *Global Change Biology,* **13**, 147-156.

Pauls, S.U., Nowak, C., Bálint, M., and Pfenninger, M., 2013: The impact of global climate change on genetic diversity within populations and species. *Molecular Ecology,* **22(4)**, 925-946.

Paun, O., Bateman, R.M., Fay, M.F., Hedren, M., Civeyrel, L., and Chase, M.W., 2010: Stable Epigenetic Effects Impact Adaptation in Allopolyploid Orchids (Dactylorhiza: Orchidaceae). *Molecular Biology and Evolution,* **27(11)**, 2465-2473.

Payette, S., 2007: Contrasted dynamics of northern Labrador tree lines caused by climate change and migrational lag. *Ecology,* **88(3)**, 770-780.

Payette, S., and Filion, L., 1985: White spruce expansion at the tree line and recent climatic change. *Canadian Journal of Forest Research,* **15(1)**, 241-251.

Pearce-Higgins, J.W., Stephen, L., Douse, A., and Langston, R.H.W., 2012: Greater impacts of wind farms on bird populations during construction than subsequent operation: results of a multi-site and multi-species analysis. *Journal of Applied Ecology,* **49(2)**, 386-394.

Pearlstine, L.G., Pearlstine, E.V., and Aumen, N.G., 2010: A review of the ecological consequences and management implications of climate change for the Everglades. *Journal of the North American Benthological Society,* **29(4)**, 1510-1526.

Pearman, P.B., Randin, C.F., Broennimann, O., Vittoz, P., van der Knaap, W.O., Engler, R., Le Lay, G., Zimmermann, N.E., and Guisan, A., 2008: Prediction of plant species distributions across six millennia. *Ecology Letters,* **11(4)**, 357-369.

Pearson, R.G., 2006: Climate change and the migration capacity of species. *Trends in Ecology & Evolution*, **21(3)**, 111-113.

Pearson, R.G., 2011: *Driven to Extinction: The Impact of Climate Change on Biodiversity*. American Museum of Natural History, Washingtonpp.

Pearson, R.G., and Dawson, T.P., 2003: Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global Ecology and Biogeography*, **12(5)**, 361-371.

Pearson, R.G., Phillips, S.J., Loranty, M.M., Beck, P.S.A., Damoulas, T., Knight, S.J., and Goetz, S.J., 2013: Arctic vegetation distribution shifts and associated feedbacks under future climate change. *Nature Climate Change*, in press.

Pederson, G.T., Graumlich, L.J., Fagre, D.B., Kipfer, T., and Muhlfeld, C.C., 2010: A century of climate and ecosystem change in Western Montana: what do temperature trends portend? *Climatic Change*, **98(1-2)**, 133-154.

Peltzer, D.A., Allen, R.B., Lovett, G.M., Whitehead, D., and Wardle, D.A., 2010: Effects of biological invasions on forest carbon sequestration. *Global Change Biology*, **16(2)**, 732-746.

Peng, C., Ma, Z., Lei, X., Zhu, Q., Chen, H., Wang, W., Liu, S., Li, W., Fang, X., and Zhou, X., 2011: A drought-induced pervasive increase in tree mortality across Canada's boreal forests. *Nature Clim. Change*, **1(9)**, 467-471.

Peng, C., Zhou, X., Zhao, S., Wang, X., Zhu, B., Piao, S., and Fang, J., 2009: Quantifying the response of forest carbon balance to future climate change in Northeastern China: model validation and prediction. *Global and Planetary Change*, **66(3-4)**, 179-194.

Penman, H.L., 1948: Natural evaporation from open water, bare soil and grass *Proceedings of the Royal Society of London. Series A: Mathematical and Physical Sciences*, **93**, 120-145.

Peñuelas, J., and Boada, M., 2003: A global change-induced biome shift in the Montseny mountains (NE Spain). *Global Change Biology*, **9(2)**, 131-140.

Peñuelas, J., Canadell, J.G., and Ogaya, R., 2011: Increased water-use efficiency during the 20th century did not translate into enhanced tree growth. *Global Ecology and Biogeography*, **20(4)**, 597-608.

Peñuelas, J., Gordon, C., Llorens, L., Nielsen, T., Tietema, A., Beier, C., Bruna, P., Emmett, B., Estiarte, M., and Gorissen, A., 2004: Nonintrusive field experiments show different plant responses to warming and drought among sites, seasons, and species in a north-south European gradient. *Ecosystems*, **7(6)**, 598-612.

Peñuelas, J., Prieto, P., Beier, C., Cesaraccio, C., de Angelis, P., de Dato, G., Emmett, B.A., Estiarte, M., Garadnai, J., Gorissen, A., Lang, E.K., Kroel-Dulay, G., Llorens, L., Pellizzaro, G., Riis-Nielsen, T., Schmidt, I.K., Sirca, C., Sowerby, A., Spano, D., and Tietema, A., 2007: Response of plant species richness and primary productivity in shrublands along a north-south gradient in Europe to seven years of experimental warming and drought: reductions in primary productivity in the heat and drought year of 2003. *Global Change Biology*, **13(12)**, 2563-2581.

Peñuelas, J., Sardans, J., Rivas-Ubach, A., and Janssens, I.A., 2012: The human-induced imbalance between C, N and P in Earth's life system. *Global Change Biology*, **18(1)**, 3-6.

Pereira, H.M., Leadley, P.W., Proenca, V., Alkemade, R., Scharlemann, J.P.W., Fernandez-Manjarres, J.F., Araujo, M.B., Balvanera, P., Biggs, R., Cheung, W.W.L., Chini, L., Cooper, H.D., Gilman, E.L., Guenette, S., Hurtt, G.C., Huntington, H.P., Mace, G.M., Oberdorff, T., Revenga, C., Rodrigues, P., Scholes, R.J., Sumaila, U.R., and Walpole, M., 2010: Scenarios for Global Biodiversity in the 21st Century. *Science*, **330(6010)**, 1496-1501.

Perry, L.G., Andersen, D.C., Reynolds, L.V., Nelson, S.M., and Shafroth, P.B., 2012: Vulnerability of riparian ecosystems to elevated CO2 and climate change in arid and semiarid western North America. *Global Change Biology*, **18(3)**, 821-842.

Peterken, G.F., and Mountford, E.P., 1996: Effects of drought on beech in Lady Park Wood, an unmanaged mixed deciduous woodland. *Forestry*, **69(2)**, 125-136.

Peterson, A.T., Stewart, A., Mohamed, K.I., and Araujo, M.B., 2008: Shifting Global Invasive Potential of European Plants with Climate Change. *PLoS One*, **3(6)**, 1-7.

Peterson, A.T.S., J., Pearson, R.G., Anderson, R.P., Martínez-Meyer, E., Nakamura, M., and Araújo, M.B., 2011: *Ecological Niches and Geographic Distributions*. Princeton University Press, Princeton, NJ, USA, 328 pp.

Petit, B., and Montagnini, F., 2006: Growth in pure and mixed plantations of tree species used in reforesting rural areas of the humid region of Costa Rica, Central America. *Forest Ecology and Management*, **233(2–3)**, 338-343.

Petitpierre, B., Kueffer, C., Broennimann, O., Randin, C., Daehler, C., and Guisan, A., 2012: Climatic Niche Shifts Are Rare Among Terrestrial Plant Invaders. *Science*, **335(6074)**, 1344-1348.

Peylin, P., Bousquet, P., Le Quere, C., Friedlingstein, P., McKinley, G., Gruber, N., Rayner, P., and Ciais, P., 2005: Multiple constraints on regional CO2 flux variations over land and oceans. *Global Biogeochemical Cycles*, **19(1)**, 1-21.

Phillimore, A.B., Hadfield, J.D., Jones, O.R., and Smithers, R.J., 2010: Differences in spawning date between populations of common frog reveal local adaptation. *Proceedings of the National Academy of Sciences of the United States of America*, **107(18)**, 8292-8297.

Phillips, O.L., Aragao, L., Lewis, S.L., Fisher, J.B., Lloyd, J., Lopez-Gonzalez, G., Malhi, Y., Monteagudo, A., Peacock, J., Quesada, C.A., van der Heijden, G., Almeida, S., Amaral, I., Arroyo, L., Aymard, G., Baker, T.R., Banki, O., Blanc, L., Bonal, D., Brando, P., Chave, J., de Oliveira, A.C.A., Cardozo, N.D., Czimczik, C.I., Feldpausch, T.R., Freitas, M.A., Gloor, E., Higuchi, N., Jimenez, E., Lloyd, G., Meir, P., Mendoza, C., Morel, A., Neill, D.A., Nepstad, D., Patino, S., Penuela, M.C., Prieto, A., Ramirez, F., Schwarz, M., Silva, J., Silveira, M., Thomas, A.S., ter Steege, H., Stropp, J., Vasquez, R., Zelazowski, P., Davila, E.A., Andelman, S., Andrade, A., Chao, K.J., Erwin, T., Di Fiore, A., Honorio, E., Keeling, H., Killeen, T.J., Laurance, W.F., Cruz, A.P., Pitman, N.C.A., Vargas, P.N., Ramirez-Angulo, H., Rudas, A., Salamao, R., Silva, N., Terborgh, J., and Torres-Lezama, A., 2009: Drought Sensitivity of the Amazon Rainforest. *Science*, **323(5919)**, 1344-1347.

Phillips, O.L., Martinez, R.V., Arroyo, L., Baker, T.R., Killeen, T., Lewis, S.L., Malhi, Y., Mendoza, A.M., Neill, D., Vargas, P.N., Alexiades, M., Ceron, C., Di Fiore, A., Erwin, T., Jardim, A., Palacios, W., Saldias, M., and Vinceti, B., 2002: Increasing dominance of large lianas in Amazonian forests. *Nature*, **418(6899)**, 770-774.

Phillips, O.L., van der Heijden, G., Lewis, S.L., Lopez-Gonzalez, G., Aragao, L.E.O.C., Lloyd, J., Malhi, Y., Monteagudo, A., Almeida, S., Alvarez Davila, E., Amaral, I., Andelman, S., Andrade, A., Arroyo, L., Aymard, G., Baker, T.R., Blanc, L., Bonal, D., Alves de Oliveira, A.C., Chao, K.-J., Davila Cardozo, N., da Costa, L., Feldpausch, T.R., Fisher, J.B., Fyllas, N.M., Freitas, M.A., Galbraith, D., Gloor, E., Higuchi, N., Honorio, E., Jimenez, E., Keeling, H., Killeen, T.J., Lovett, J.C., Meir, P., Mendoza, C., Morel, A., Nunez Vargas, P., Patino, S., Peh, K.S.H., Pena Cruz, A., Prieto, A., Quesada, C.A., Ramirez, F., Ramirez, H., Rudas, A., Salamao, R., Schwarz, M., Silva, J., Silveira, M., Slik, J.W.F., Sonke, B., Thomas, A.S., Stropp, J., Taplin, J.R.D., Vasquez, R., and Vilanova, E., 2010: Drought-mortality relationships for tropical forests. *New Phytologist*, **187(3)**, 631-646.

Phillips, O.L., Vásquez Martínez, R., Monteagudo Mendoza, A., Baker, T., and Núñez-Vargas, P., 2005: Large lianas as hyperdynamic elements of the tropical forest canopy. *Ecology*, **86(5)**, 1250-1258.

Pielke, R.A., Pitman, A., Niyogi, D., Mahmood, R., McAlpine, C., Hossain, F., Goldewijk, K.K., Nair, U., Betts, R., Fall, S., Reichstein, M., Kabat, P., and de Noblet, N., 2011: Land use/land cover changes and climate: modeling analysis and observational evidence. *Wiley Interdisciplinary Reviews-Climate Change*, **2(6)**, 828-850.

Pitman, A.J., de Noblet-Ducoudre, N., Cruz, F.T., Davin, E.L., Bonan, G.B., Brovkin, V., Claussen, M., Delire, C., Ganzeveld, L., Gayler, V., van den Hurk, B.J.J.M., Lawrence, P.J., van der Molen, M.K., Muller, C., Reick, C.H., Seneviratne, S.I., Strengers, B.J., and Voldoire, A., 2009: Uncertainties in climate responses to past land cover change: First results from the LUCID intercomparison study. *Geophysical Research Letters*, **36(L08702)**, 1-6.

Pitman, A.J., Narisma, G.T., and McAneney, J., 2007: The impact of climate change on the risk of forest and grassland fires in Australia. *Climatic Change*, **84(3-4)**, 383-401.

Ponniah, M., and Hughes, J.M., 2004: The evolution of Queensland spiny mountain crayfish of the genus Euastacus. I. Testing vicariance and dispersal with interspecific mitochondrial DNA. *Evolution*, **58(5)**, 1073-1085.

Porter, T.J., and Pisaric, M.F.J., 2011: Temperature-growth divergence in white spruce forests of Old Crow Flats, Yukon Territory, and adjacent regions of northwestern North America. *Global Change Biology*, **17(11)**, 3418-3430.

Post, E., Forchhammer, M.C., Bret-Harte, M.S., Callaghan, T.V., Christensen, T.R., Elberling, B., Fox, A.D., Gilg, O., Hik, D.S., Hoye, T.T., Ims, R.A., Jeppesen, E., Klein, D.R., Madsen, J., McGuire, A.D., Rysgaard, S., Schindler, D.E., Stirling, I., Tamstorf, M.P., Tyler, N.J.C., van der Wal, R., Welker, J., Wookey, P.A., Schmidt, N.M., and Aastrup, P., 2009: Ecological Dynamics Across the Arctic Associated with Recent Climate Change. *Science*, **325(5946)**, 1355-1358.

Post, E., Pedersen, C., Wilmers, C.C., and Forchhammer, M.C., 2008: Warming, plant phenology and the spatial dimension of trophic mismatch for large herbivores. *Proceedings of the Royal Society B: Biological Sciences*, **275(1646)**, 2005-2013.

Potts, S.G., Biesmeijer, J.C., Kremen, C., Neumann, P., Schweiger, O., and Kunin, W.E., 2010: Global pollinator declines: trends, impacts and drivers. *Trends in Ecology & Evolution*, **25(6)**, 345-353.

Potvin, C., Chapin, F., Gonzalez, A., Leadley, P., Reich, P., and Roy, J., 2007: Plant Biodiversity and Responses to Elevated Carbon Dioxide. In *Terrestrial Ecosystems in a Changing World. Global Change* [J. G. Canadell, D. E. Pataki & L. F. Pitelka (eds.)]. Springer, Berlin, pp. 103-112.

Pounds, J.A., Bustamante, M.R., Coloma, L.A., Consuegra, J.A., Fogden, M.P.L., Foster, P.N., La Marca, E., Masters, K.L., Merino-Viteri, A., Puschendorf, R., Ron, S.R., Sanchez-Azofeifa, G.A., Still, C.J., and Young, B.E., 2006: Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature*, **439(7073)**, 161-167.

Prentice, I.C., Guiot, J., Huntley, B., Jolly, D., and Cheddadi, R., 1996: Reconstructing biomes from palaeoecological data: a general method and its application to European pollen data at 0 and 6 ka. *Climate Dynamics*, **12**, 185-194.

Prentice, I.C., and Harrison, S.P., 2009: Ecosystem effects of CO(2) concentration: evidence from past climates. *Climate of the Past*, **5(3)**, 297-307.

Prentice, I.C., Harrison, S.P., and Bartlein, P.J., 2011: Global vegetation and terrestrial carbon cycle changes after the last ice age. *New Phytologist*, **189(4)**, 988-998.

Prieto, P., Penuelas, J., Llusia, J., Asensio, D., and Estiarte, M., 2009: Effects of long-term experimental night-time warming and drought on photosynthesis, Fv/Fm and stomatal conductance in the dominant species of a Mediterranean shrubland. *Acta Physiologiae Plantarum*, **31(4)**, 729-739.

Primack, R.B., Ibáñez, I., Higuchi, H., Lee, S.D., Miller-Rushing, A.J., Wilson, A.M., and Silander Jr, J.A., 2009: Spatial and interspecific variability in phenological responses to warming temperatures. *Biological Conservation*, **142(11)**, 2569-2577.

Prince, S.D., Wessels, K.J., Tucker, C.J., and Nicholson, S.E., 2007: Desertification in the Sahel: A reinterpretation of a reinterpretation. *Global Change Biology*, **13(7)**, 1308-1313.

Pringle, C.M., 2001: Hydrologic connectivity and the management of biological reserves: A global perspective. *Ecological Applications*, **11(4)**, 981-998.

Prowse, T.D., and Brown, K., 2010: Hydro-ecological effects of changing Arctic river and lake ice covers: a review. *Hydrology Research*, **41(6)**, 454-461.

Prugh, L.R., Hodges, K.E., Sinclair, A.R.E., and Brashares, J.S., 2008: Effect of habitat area and isolation on fragmented animal populations. *Proceedings of the National Academy of Sciences of the United States of America*, **105(52)**, 20770-20775.

Pulido, F., 2007: Phenotypic changes in spring arrival: evolution, phenotypic plasticity, effects of weather and condition. *Climate Research*, **35(1-2)**, 5-23.

Racine, C., Jandt, R., Meyers, C., and Dennis, J., 2004: Tundra fire and vegetation change along a hillslope on the Seward Peninsula, Alaska, U.S.A. *Arctic, Antarctic, and Alpine Research*, **36(1)**, 1-10.

Raffa, K.F., Aukema, B.H., Bentz, B.J., Carroll, A.L., Hicke, J.A., Turner, M.G., and Romme, W.H., 2008: Cross-scale Drivers of Natural Disturbances Prone to Anthropogenic Amplification: The Dynamics of Bark Beetle Eruptions. *Bioscience*, **58(6)**, 501-517.

Rahel, F.J., and Olden, J.D., 2008: Assessing the effects of climate change on aquatic invasive species. *Conservation Biology*, **22(3)**, 521-533.

Randerson, J.T., Liu, H., Flanner, M.G., Chambers, S.D., Jin, Y., Hess, P.G., Pfister, G., Mack, M.C., Treseder, K.K., Welp, L.R., Chapin, F.S., Harden, J.W., Goulden, M.L., Lyons, E., Neff, J.C., Schuur, E.A.G., and Zender, C.S., 2006: The impact of boreal forest fire on climate warming. *Science*, **314(5802)**, 1130-1132.

Randin, C.F., Engler, R., Normand, S., Zappa, M., Zimmermann, N.E., Pearman, P.B., Vittoz, P., Thuiller, W., and Guisan, A., 2009: Climate change and plant distribution: local models predict high-elevation persistence. *Global Change Biology*, **15(6)**, 1557-1569.

Raupach, M.R., Canadell, J.G., and Le QuÃ©rÃ©, C., 2008: Anthropogenic and biophysical contributions to increasing atmospheric CO2 growth rate and airborne fraction. *Biogeosciences*, **5(6)**, 2867-2896.

Ravi, S., Breshears, D.D., Huxman, T.E., and D'Odorico, P., 2010: Land degradation in drylands: Interactions among hydrologic-aeolian erosion and vegetation dynamics. *Geomorphology*, **116(3-4)**, 236-245.

Raxworthy, C.J., Pearson, R.G., Rabibisoa, N., Rakotondrazafy, A.M., Ramanamanjato, J.B., Raselimanana, A.P., Wu, S., Nussbaum, R.A., and Stone, D.A., 2008: Extinction vulnerability of tropical montane endemism from warming and upslope displacement: a preliminary appraisal for the highest massif in Madagascar. *Global Change Biology*, **14(8)**, 1703-1720.

Ray, D., Nepstad, D., and Moutinho, P., 2005: Micrometeorological and canopy controls of flammability in mature and disturbed forests in an east-central Amazon landscape. *Ecological Applications,* **15(5)**, 1664-1678.

Ray, D.K., Ramankutty, N., Mueller, N.D., West, P.C., and Foley, J.A., 2012: Recent patterns of crop yield growth and stagnation. *Nat Commun,* **3**, 1293.

Réale, D., McAdam, A.G., Boutin, S., and Berteaux, D., 2003: Genetic and plastic responses of a northern mammal to climate change. *Proceedings of the Royal Society of London. Series B: Biological Sciences,* **270(1515)**, 591-596.

Regnier, C., Fontaine, B., and Bouchet, P., 2009: Not Knowing, Not Recording, Not Listing: Numerous Unnoticed Mollusk Extinctions. *Conservation Biology,* **23(5)**, 1214-1221.

Reich, P.B., 2009: Elevated CO2 Reduces Losses of Plant Diversity Caused by Nitrogen Deposition. *Science,* **326(5958)**, 1399-1402.

Reist, J.D., Wrona, F.J., Prowse, T.D., Power, M., Dempson, J.B., Beamish, R.J., King, J.R., Carmichael, T.J., and Sawatzky, C.D., 2006: General effects of climate change on Arctic fishes and fish populations. *Ambio,* **35(7)**, 370-380.

Renwick, A.R., Massimino, D., Newson, S.E., Chamberlain, D.E., Pearce-Higgins, J.W., and Johnston, A., 2012: Modelling changes in species' abundance in response to projected climate change. *Diversity and Distributions,* **18(2)**, 121-132.

Ricciardi, A., and Simberloff, D., 2009: Assisted colonization is not a viable conservation strategy. *Trends in Ecology & Evolution,* **24(5)**, 248-253.

Ridgwell, A., Singarayer, J.S., Hetherington, A.M., and Valdes, P.J., 2009: Tackling regional climate change by leaf albedo bio-geoengineering. *Current Biology,* **19(2)**, 146-150.

Rieley, J.O., Wüst, R.A.J., Jauhiainen, J., Page, S.E., Wösten, J.H.M., Hooijer, A., Siegert, E., Limin, S.H., Vasander, H., and Stahlhut, M., 2008: Tropical peatlands: carbon stores, carbon gas emissions and contribution to climate change processes. In *Peatlands and climate change* [M. Strack (ed.)]. International Peat Society, Jyväskylä, pp. 148-181.

Roberts, S.P.M., Potts, S.G., Biesmeijer, J., Kuhlmann, M., Kunin, B., and Ohlemüller, R., 2011: Assessing continental-scale risks for generalist and specialist pollinating bee species under climate change. *BioRisk,* **6**, 1-18.

Robinet, C., and Roques, A., 2010: Direct impacts of recent climate warming on insect populations. *Integrative Zoology,* **5(2)**, 132-142.

Rocha, A.V., and Shaver, G.R., 2011: Burn severity influences postfire CO2 exchange in arctic tundra. *Ecological Applications,* **21(2)**, 477-489.

Rodriguez-Labajos, B., submitted: Climate and change, ecosystems services and costs of action and inaction. Scoping the interface. *WIREs Climate Change*.

Rohde, R.F., and Hoffman, M.T., 2012: The historical ecology of Namibian rangelands: Vegetation change since 1876 in response to local and global drivers. . *Science of The Total Environment,* **416**, 276-288.

Romanovsky, V.E., Smith, S.L., and Christiansen, H.H., 2010: Permafrost Thermal State in the Polar Northern Hemisphere during the International Polar Year 2007-2009: a Synthesis. *Permafrost and Periglacial Processes,* **21(2)**, 106-116.

Romijn, E., Herold, M., Kooistra, L., Murdiyarso, D., and Verchot, L., 2012: Assessing capacities of non-Annex I countries for national forest monitoring in the context of REDD+. *Environmental Science and Policy,* **19-20**, 33-48.

Rosenheim, J.A., and Tabashnik, B.E., 1991: Influence of generation time on the response to selection. *American Naturalist,* **137(4)**, 527-541.

Rosset, V., Lehmann, A., and Oertli, B., 2010: Warmer and richer? Predicting the impact of climate warming on species richness in small temperate waterbodies. *Global Change Biology,* **16(8)**, 2376-2387.

Rössler, M., 2006: World heritage cultural landscapes: A UNESCO flagship programme 1992-2006. *Landscape Research,* **31(4)**, 333-353.

Rounsevell, M.D.A., and Reay, D.S., 2009: Land use and climate change in the UK. *Land Use Policy,* **26(0)**, S160-S169.

Roux, D.J., Nel, J.L., Ashton, P.J., Deaconc, A.R., de Moor, F.C., Hardwick, D., Hill, L., Kleynhans, C.J., Maree, G.A., Moolman, J., and Scholes, R.J., 2008: Designing protected areas to conserve riverine biodiversity: Lessons from a hypothetical redesign of the Kruger National Park. *Biological Conservation,* **141(1)**, 100-117.

Rowe, R.J., Finarelli, J.A., and Rickart, E.A., 2010: Range dynamics of small mammals along an elevational gradient over an 80-year interval. *Global Change Biology,* **16(11)**, 2930-2943.

Rubidge, E.M., Monahan, W.B., Parra, J.L., Cameron, S.E., and Brashares, J.S., 2011: The role of climate, habitat, and species co-occurrence as drivers of change in small mammal distributions over the past century. *Global Change Biology,* **17(2)**, 696-708.

Ruiz-Labourdette, D., Schmitz, M.F., and Pineda, F.D., 2013: Changes in tree species composition in Mediterranean mountains under climate change: Indicators for conservation planning. *Ecological Indicators,* **24**, 310-323.

Rupp, T.S., Chapin, F.S., and Starfield, A., 2001: Modeling the Influence of Topographic Barriers on Treeline Advance at the Forest-Tundra Ecotone in Northwestern Alaska. *Climatic Change,* **48(2)**, 399-416.

Rustad, L., 2001: Global change - Matter of time on the prairie. *Nature,* **413(6856)**, 578-579.

Rustad, L.E., 2008: The response of terrestrial ecosystems to global climate change: Towards an integrated approach. *Science of the Total Environment,* **404(2–3)**, 222-235.

Ryan, M.G., Harmon, M.E., Birdsey, R.A., Giardina, C.P., Heath, L.S., Houghton, R.A., Jackson, R.B., McKinley, D.C., Morrison, J.F., Murray, B.C., Pataki, D.E., and Skog, K.E., 2010: A Synthesis of the Science on Forests and Carbon for U.S. Forests. *Issues in Ecology,* **13**, 1-17.

Saatchi, S., Asefi-Najafabady, S., Malhi, Y., Aragão, L.E.O.C., Anderson, L.O., Myneni, R.B., and Nemani, R., 2013: Persistent effects of a severe drought on Amazonian forest canopy. *Proceedings of the National Academy of Sciences,* **110(2)**, 565-570.

Saino, N., Rubolini, D., Lehikoinen, E., Sokolov, L.V., Bonisoli-Alquati, A., Ambrosini, R., Boncoraglio, G., and Moller, A.P., 2009: Climate change effects on migration phenology may mismatch brood parasitic cuckoos and their hosts. *Biology Letters,* **5(4)**, 539-541.

Sala, O.E., Parton, W.J., Joyce, L.A., and Lauenroth, W.K., 1988: Primary Production of the Central Grassland Region of the United States. *Ecology,* **69(1)**, 10-45.

Salamin, N., Wuest, R.O., Lavergne, S., Thuiller, W., and Pearman, P.B., 2010: Assessing rapid evolution in a changing environment. *Trends in Ecology & Evolution,* **25(12)**, 692-698.

Salazar, L.F., Nobre, C.A., and Oyama, M.D., 2007: Climate change consequences on the biome distribution in tropical South America. *Geophysical Research Letters,* **34(L09708)**, 1-6.

Salzmann, U., Haywood, A.M., Lunt, D.J., Valdes, P.J., and Hill, D.J., 2008: A new global biome reconstruction and data-model comparison for the Middle Pliocene. *Global Ecology and Biogeography,* **17(3)**, 432-447.

Samanta, A., Costa, M.H., Nunes, E.L., Vieira, S.A., Xu, L., and Myneni, R.B., 2011: Comment on "Drought-Induced Reduction in Global Terrestrial Net Primary Production from 2000 Through 2009". *Science,* **333(6046)**.

Sampaio, G., Nobre, C., Costa, M.H., Satyamurty, P., Soares, B.S., and Cardoso, M., 2007: Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion. *Geophysical Research Letters,* **34(L17709)**, 1-7.

Sandel, B., Arge, L., Dalsgaard, B., Davies, R.G., Gaston, K.J., Sutherland, W.J., and Svenning, J.C., 2011: The Influence of Late Quaternary Climate-Change Velocity on Species Endemism. *Science,* **334(6056)**, 660-664.

Sandel, B., and Dangremond, E.M., 2012: Climate change and the invasion of California by grasses. *Global Change Biology,* **18(1)**, 277-289.

Sankaran, M., Hanan, N.P., Scholes, R.J., Ratnam, J., Augustine, D.J., Cade, B.S., Gignoux, J., Higgins, S.I., Le Roux, X., Ludwig, F., Ardo, J., Banyikwa, F., Bronn, A., Bucini, G., Caylor, K.K., Coughenour, M.B., Diouf, A., Ekaya, W., Feral, C.J., February, E.C., Frost, P.G.H., Hiernaux, P., Hrabar, H., Metzger, K.L., Prins, H.H.T., Ringrose, S., Sea, W., Tews, J., Worden, J., and Zambatis, N., 2005: Determinants of woody cover in African savannas. *Nature,* **438(7069)**, 846-849.

Saraux, C., Le Bohec, C., Durant, J.M., Viblanc, V.A., Gauthier-Clerc, M., Beaune, D., Park, Y.-H., Yoccoz, N.G., Stenseth, N.C., and Le Maho, Y., 2011: Reliability of flipper-banded penguins as indicators of climate change. *Nature,* **469(7329)**, 203-206.

Sarris, D., Christodoulakis, D., and Körner, C., 2011: Impact of recent climatic change on growth of low elevation eastern Mediterranean forest trees. *Climatic Change,* **106(2)**, 203-223.

Sato, H., and Ise, T., 2012: Effect of plant dynamic processes on African vegetation responses to climate change: Analysis using the spatially explicit individual-based dynamic global vegetation model (SEIB-DGVM). *Journal of Geophysical Research-Biogeosciences,* **117**.

Satterthwaite, D., 2008: Cities' contribution to global warming: notes on the allocation of greenhouse gas emissions. *Environment and Urbanization,* **20(2)**, 539-549.

Sauer, J., Domisch, S., Nowak, C., and Haase, P., 2011: Low mountain ranges: summit traps for montane freshwater species under climate change. *Biodiversity and Conservation*, **20(13)**, 3133-3146.

Saurral, R.I., Barros, V.R., and Lettenmaier, D.P., 2008: Land use impact on the Uruguay River discharge. *Geophys. Res. Lett.*, **35(12)**, L12401.

Schaefer, K., Zhang, T.J., Bruhwiler, L., and Barrett, A.P., 2011: Amount and timing of permafrost carbon release in response to climate warming. *Tellus Series B-Chemical and Physical Meteorology*, **63(2)**, 165-180.

Schaper, S.V., Dawson, A., Sharp, P.J., Gienapp, P., Caro, S.P., and Visser, M.E., 2012: Increasing Temperature, Not Mean Temperature, Is a Cue for Avian Timing of Reproduction. *The American Naturalist*, **179(2)**, E55-E69.

Scheffer, M., 2009: *Critical transitions in nature and society*. Princeton University Press, Princeton, New Jersey, 400 pp.

Scheffer, M., Bascompte, J., Brock, W.A., Brovkin, V., Carpenter, S.R., Dakos, V., Held, H., van Nes, E.H., Rietkerk, M., and Sugihara, G., 2009: Early-warning signals for critical transitions. *Nature*, **461(7260)**, 53-59.

Scheffer, M., Hirota, M., Holmgren, M., Van Nes, E.H., and Chapin, F.S., III, 2012: Thresholds for boreal biome transitions. *Proceedings of the National Academy of Sciences of the United States of America*, **109(52)**, 21384-21389.

Scheiter, S., and Higgins, S.I., 2009: Impacts of climate change on the vegetation of Africa: an adaptive dynamic vegetation modelling approach. *Global Change Biology*, **15(9)**, 2224-2246.

Schiffers, K., Bourne, E.C., Lavergne, S., Thuiller, W., and Travis, J.M.J., 2013: Limited evolutionary rescue of locally adapted populations facing climate change. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **368(1610)**.

Schippers, P., Verboom, J., Vos, C.C., and Jochem, R., 2011: Metapopulation shift and survival of woodland birds under climate change: will species be able to track? *Ecography*, **34(6)**, 909-919.

Schloss, C.A., Nunez, T.A., and Lawler, J.J., 2012: Dispersal will limit ability of mammals to track climate change in the Western Hemisphere. *Proceedings of the National Academy of Sciences of the United States of America*, **109(22)**, 8606-8611.

Schneider, A., Friedl, M.A., and Potere, D., 2009: A new map of global urban extent from MODIS satellite data. *Environmental Research Letters*, **4(4)**.

Schnitzler, A., Hale, B.W., and Alsum, E.M., 2007: Examining native and exotic species diversity in European riparian forests. *Biological Conservation*, **138(1-2)**, 146-156.

Scholes, R.J., and Archer, S.R., 1997: Tree-grass interactions in savannas. *Annual Review of Ecology and Systematics*, **28**, 517-544.

Scholze, M., Knorr, W., Arnell, N.W., and Prentice, I.C., 2006: A climate-change risk analysis for world ecosystems. *Proceedings of the National Academy of Sciences*, **103(35)**, 13116-13120.

Schulte, P., Alegret, L., Arenillas, I., Arz, J.A., Barton, P.J., Bown, P.R., Bralower, T.J., Christeson, G.L., Claeys, P., Cockell, C.S., Collins, G.S., Deutsch, A., Goldin, T.J., Goto, K., Grajales-Nishimura, J.M., Grieve, R.A.F., Gulick, S.P.S., Johnson, K.R., Kiessling, W., Koeberl, C., Kring, D.A., MacLeod, K.G., Matsui, T., Melosh, J., Montanari, A., Morgan, J.V., Neal, C.R., Nichols, D.J., Norris, R.D., Pierazzo, E., Ravizza, G., Rebolledo-Vieyra, M., Reimold, W.U., Robin, E., Salge, T., Speijer, R.P., Sweet, A.R., Urrutia-Fucugauchi, J., Vajda, V., Whalen, M.T., and Willumsen, P.S., 2010: The Chicxulub Asteroid Impact and Mass Extinction at the Cretaceous-Paleogene Boundary. *Science*, **327(5970)**, 1214-1218.

Schultz, M.G., Heil, A., Hoelzemann, J.J., Spessa, A., Thonicke, K., Goldammer, J.G., Held, A.C., Pereira, J.M.C., and van het Bolscher, M., 2008: Global wildland fire emissions from 1960 to 2000. *Global Biogeochemical Cycles*, **22(2)**, 2002.

Schuur, E.A.G., Bockheim, J., Canadell, J.G., Euskirchen, E., Field, C.B., Goryachkin, S.V., Hagemann, S., Kuhry, P., Lafleur, P.M., Lee, H., Mazhitova, G., Nelson, F.E., Rinke, A., Romanovsky, V.E., Shiklomanov, N., Tarnocai, C., Venevsky, S., Vogel, J.G., and Zimov, S.A., 2008: Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle. *Bioscience*, **58(8)**, 701-714.

Schuur, E.A.G., Vogel, J.G., Crummer, K.G., Lee, H., Sickman, J.O., and Osterkamp, T.E., 2009: The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. *Nature*, **459(7246)**, 556-559.

Schwaiger, H.P., and Bird, D.N., 2010: Integration of albedo effects caused by land use change into the climate balance: Should we still account in greenhouse gas units? *Forest Ecology and Management*, **260(3)**, 278-286.

Schweiger, O., Biesmeijer, J.C., Bommarco, R., Hickler, T., Hulme, P.E., Klotz, S., Kuehn, I., Moora, M., Nielsen, A., Ohlemüller, R., Petanidou, T., Potts, S.G., Pyšek, P., Stout, J.C., Sykes, M.T., Tscheulin, T., Vila, M., Walther, G.-R., Westphal, C., Winter, M., Zobel, M., and Settele, J., 2010: Multiple stressors on biotic interactions: how climate change and alien species interact to affect pollination. *Biological Reviews,* **85(4)**, 777-795.

Schweiger, O., Harpke, A., Heikkinen, R., Hickler, T., Kühn, I., Pöyry, J., and Settele, J., 2012: Increasing range mismatching of interacting species under global change is related to their ecological characteristics. *Global Ecology and Biogeography,* **21(1)**, 88-99.

Schweiger, O., Settele, J., Kudrna, O., Klotz, S., and Kühn, I., 2008: Climate change can cause spatial mismatch of trophically interacting species. *Ecology,* **89(12)**, 3472-3479.

Schwilk, D.W., and Keeley, J.E., 2012: A Plant Distribution Shift: Temperature, Drought or Past Disturbance? *PLoS One,* **7(2)**.

Seaquist, J.W., Hickler, T., Eklundh, L., Ardo, J., and Heumann, B.W., 2009: Disentangling the effects of climate and people on Sahel vegetation dynamics. *Biogeosciences,* **6(3)**, 469-477.

Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F.X., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., and Yu, T.H., 2008: Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science,* **319(5867)**, 1238-1240.

Secretariat of the Convention on Biological Diversity, 2010: *Global Biodiversity Outlook 3.* Montréal, 94 pp.

Seidel, D.J., Fu, Q., Randel, W.J., and Reichler, T.J., 2008: Widening of the tropical belt in a changing climate. *Nature Geoscience,* **1(1)**, 21-24.

Sekar, S., 2012: A meta-analysis of the traits affecting dispersal ability in butterflies: can wingspan be used as a proxy? *Journal of Animal Ecology,* **81(1)**, 174-184.

Sekercioglu, C.H., Primack, R.B., and Wormworth, J., 2012: The effects of climate change on tropical birds. *Biological Conservation,* **148(1)**, 1-18.

Selsted, M.B., van der Linden, L., Ibrom, A., Michelsen, A., Larsen, K.S., Pedersen, J.K., Mikkelsen, T.N., Pilegaard, K., Beier, C., and Ambus, P., 2012: Soil respiration is stimulated by elevated CO2 and reduced by summer drought: three years of measurements in a multifactor ecosystem manipulation experiment in a temperate heathland (CLIMAITE). *Global Change Biology,* **18(4)**, 1216-1230.

Seppälä, R., 2009: A global assessment on adaptation of forests to climate change. *Scandinavian Journal of Forest Research,* **24(6)**, 469-472.

Serreze, M.C., and Francis, J.A., 2006: The Arctic amplification debate. *Climate Change,* **76(3)**, 241-264.

Settele, J., Kudrna, O., Harpke, A., Kühn, I., Van Swaay, C., Verovnik, R., Warren, M., Wiemers, M., Hanspach, J., Hickler, T., Kühn, E., Van Halder, I., Veling, K., Vliegenthart, A., Wynhoff, I., and Schweiger, O., 2008: Climatic risk atlas of European butterflies. *BioRisk,* **1**, 1-710.

Settele, J., and Kühn, E., 2009: Insect Conservation. *Science,* **325(5936)**, 41-42.

Settele, J., Penev, L., Georgiev, T., Grabaum, R., Grobelnik, V., Hammen, V., Klotz, S., Kotarac, M., and Kühn, I. (eds.), 2010a: *Atlas of Biodiversity Risk*. Pensoft, Sofia, Moscow, pp. 300.

Settele, J., Zobel, M., Spangenberg, J.H., Klotz, S., Hammen, V., and Kühn, I., 2010b: Designing Projects for Integrated Research – The ALARM Experience. In *Atlas of Biodiversity Risk. Pensoft* [J. Settele, L. Penev, T. Georgiev, R. Grabaum, V. Grobelnik, V. Hammen, S. Klotz, M. Kotarac & I. Kühn (eds.)]. Pensoft, Sofia, Moscow, pp. 208-209.

Shanin, V.N., Komarov, A.S., Mikhailov, A.V., and Bykhovets, S.S., 2011: Modelling carbon and nitrogen dynamics in forest ecosystems of Central Russia under different climate change scenarios and forest management regimes. *Ecological Modelling,* **222(14)**, 2262-2275.

Sharma, S., Couturier, S., and Cote, S.D., 2009: Impacts of climate change on the seasonal distribution of migratory caribou. *Global Change Biology,* **15(10)**, 2549-2562.

Sharp, B.R., and Bowman, D.M.J.S., 2004: Patterns of long-term woody vegetation change in a sandstone-plateau savanna woodland, Northern Territory, Australia. *Journal of Tropical Ecology,* **20(03)**, 259-270.

Shaw, M.R., Pendleton, L., Cameron, D.R., Morris, B., Bachelet, D., Klausmeyer, K., MacKenzie, J., Conklin, D.R., Bratman, G.N., Lenihan, J., Haunreiter, E., Daly, C., and Roehrdanz, P.R., 2011: The impact of climate change on California's ecosystem services. *Climatic Change,* **109(3-4)**, 465-484.

Shaw, M.R., Zavaleta, E.S., Chiariello, N.R., Cleland, E.E., Mooney, H.A., and Field, C.B., 2002: Grassland responses to global environmental changes suppressed by elevated CO2. *Science,* **298(5600)**, 1987-1990.

Sheldon, F., Bunn, S.E., Hughes, J.M., Arthington, A.H., Balcombe, S.R., and Fellows, C.S., 2010: Ecological roles and threats to aquatic refugia in arid landscapes: dryland river waterholes. *Marine and Freshwater Research,* **61(8)**, 885-895.

Shimoda, Y., Azim, M.E., Perhar, G., Ramin, M., Kenney, M.A., Sadraddini, S., Gudimov, A., and Arhonditsis, G.B., 2011: Our current understanding of lake ecosystem response to climate change: What have we really learned from the north temperate deep lakes? *Journal of Great Lakes Research*, **37(1)**, 173-193.

Shinoda, M., Nachinshonhor, G.U., and Nemoto, M., 2010: Impact of drought on vegetation dynamics of the Mongolian steppe: A field experiment. *Journal of Arid Environments*, **74(1)**, 63-69.

Shiogama, H., Emori, S., Hanasaki, N., Abe, M., Masutomi, Y., Takahashi, K., and Nozawa, T., 2011: Observational constraints indicate risk of drying in the Amazon basin. *Nature Communications*, **2**.

Silva, L.C.R., and Anand, M., 2013: Probing for the influence of atmospheric CO2 and climate change on forest ecosystems across biomes. *Global Ecology and Biogeography*, **22(1)**, 83-92.

Silva, L.C.R., Anand, M., and Leithead, M.D., 2010: Recent Widespread Tree Growth Decline Despite Increasing Atmospheric CO2. *PLoS One*, **5(7)**, 1-7.

Silvestrini, R., Soares-Filho, B., Nepstad, D., Coe, M.T., Rodrigues, H., and Assuncao, R., 2011: Simulating fire regimes in the Amazon in response to climate change and deforestation. *Ecological Applications*, **21(5)**, 1573-1590.

Simberloff, D., Martin, J.-L., Genovesi, P., Maris, V., Wardle, D.A., Aronson, J., Courchamp, F., Galil, B., García-Berthou, E., Pascal, M., Pyšek, P., Sousa, R., Tabacchi, E., and Vilà, M., 2013: Impacts of biological invasions: what's what and the way forward. *Trends in Ecology & Evolution*, **28(1)**, 58-66.

Sinervo, B., Mendez-de-la-Cruz, F., Miles, D.B., Heulin, B., Bastiaans, E., Cruz, M.V.S., Lara-Resendiz, R., Martinez-Mendez, N., Calderon-Espinosa, M.L., Meza-Lazaro, R.N., Gadsden, H., Avila, L.J., Morando, M., De la Riva, I.J., Sepulveda, P.V., Rocha, C.F.D., Ibarguengoytia, N., Puntriano, C.A., Massot, M., Lepetz, V., Oksanen, T.A., Chapple, D.G., Bauer, A.M., Branch, W.R., Clobert, J., and Sites, J.W., 2010: Erosion of Lizard Diversity by Climate Change and Altered Thermal Niches. *Science*, **328(5980)**, 894-899.

Singer, M.C., and Parmesan, C., 2010: Phenological asynchrony between herbivorous insects and their hosts: signal of climate change or pre-existing adaptive strategy? *Philosophical Transactions of the Royal Society B-Biological Sciences*, **365(1555)**, 3161-3176.

Singh, A., Unnikrishnan, S., Naik, N., and Duvvuri, K., 2013: Role of India´s forest in climate change mitigation through the CDM and REDD+. *Journal of Environmental Planning and Management*, **56**, 61-87.

Sitch, S., Cox, P.M., Collins, W.J., and Huntingford, C., 2007: Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. *Nature*, **448(7155)**, 791-U794.

Sitch, S., Huntingford, C., Gedney, N., Levy, P.E., Lomas, M., Piao, S.L., Betts, R., Ciais, P., Cox, P., Friedlingstein, P., Jones, C.D., Prentice, I.C., and Woodward, F.I., 2008: Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs). *Global Change Biology*, **14(9)**, 2015-2039.

Smallwood, K.S., 2007: Estimating Wind Turbine-Caused Bird Mortality. *Journal of Wildlife Management*, **71(8)**, 2781-2791.

Smit, B., Burton, I., Klein, R.J.T., and Wandel, J., 2000: An anatomy of adaptation to climate change and variability. *Climatic Change*, **45(1)**, 223-251.

Smit, B., Pilifosova, O., Burton, I., Challenger, B., Huq, S., Klein, R.J.T., Yohe, G., Adger, N., Downing, T., Harvey, E., Kane, S., Parry, M., Skinner, M., Smith, J., and Wandel, J., 2007: Adaptation to Climate Change in the Context of Sustainable Development and Equity. In *Third Assessment Report WG II*. Intergovernmental panel on Climate Change, Geneva, pp. 879-912.

Smith, A.L., Hewitt, N., Klenk, N., Bazely, D.R., Yan, N., Wood, S., Henriques, I., MacLellan, J.I., and Lipsig-Mummé, C., 2012: Effects of climate change on the distribution of invasive alien species in Canada: a knowledge synthesis of range change projections in a warming world. *Environmental Reviews*, **20(1)**, 1-16.

Smith, L.C., Sheng, Y., MacDonald, G.M., and Hinzman, L.D., 2005: Disappearing Arctic lakes. *Science*, **308(5727)**, 1429-1429.

Smol, J.P., and Douglas, M.S.V., 2007a: Crossing the final ecological threshold in high Arctic ponds. *Proceedings of the National Academy of Sciences of the United States of America*, **104(30)**, 12395-12397.

Smol, J.P., and Douglas, M.S.V., 2007b: From controversy to consensus: making the case for recent climate using lake sediments. *Frontiers in Ecology and the Environment*, **5(9)**, 466-474.

Snyman, H.A., and Fouché, H.J., 1993: Estimating seasonal herbage production of a semi-arid grassland based on veld condition, rainfall, and evapotranspiration. *African Journal of Range and Forage Science*, **10(1)**, 21-24.

Soares-Filho, B., Moutinho, P., Nepstad, D., Anderson, A., Rodrigues, H., Garcia, R., Dietzsch, L., Merry, F., Bowman, M., Hissa, L., Silvestrini, R., and Maretti, C., 2010: Role of Brazilian Amazon protected areas in climate change mitigation. *Proceedings of the National Academy of Sciences,* **107(24)**, 10821-10826.

Soares-Filho, B., Silvestrini, R., Nepstad, D., Brando, P., Rodrigues, H., Alencar, A., Coe, M., Locks, C., Lima, L., Hissa, L., and Stickler, C., 2012: Forest fragmentation, climate change and understory fire regimes on the Amazonian landscapes of the Xingu headwaters. *Landscape Ecology,* **27(4)**, 585-598.

Sobek-Swant, S., Crosthwaite, J.C., Lyons, D.B., and Sinclair, B.J., 2012: Could phenotypic plasticity limit an invasive species? Incomplete reversibility of mid-winter deacclimation in emerald ash borer. *Biological Invasions,* **14(1)**, 115-125.

Sodhi, N.S., Bickford, D., Diesmos, A.C., Lee, T.M., Koh, L.P., Brook, B.W., Sekercioglu, C.H., and Bradshaw, C.J.A., 2008: Measuring the Meltdown: Drivers of Global Amphibian Extinction and Decline. *PLoS One,* **3(2)**, 8.

Soja, A.J., Tchebakova, N.M., French, N.H.F., Flannigan, M.D., Shugart, H.H., Stocks, B.J., Sukhinin, A.I., Parfenova, E.I., Chapin, F.S., and Stackhouse, P.W., 2007: Climate-induced boreal forest change: Predictions versus current observations. *Global and Planetary Change,* **56(3-4)**, 274-296.

Sokolov, L., 2006: Effect of global warming on the timing of migration and breeding of passerine birds in the 20th century. *Entomological Review Supplement,* **86(1)**, S59-S81.

Soliani, C., Gallo, L., and Marchelli, P., 2012: Phylogeography of two hybridizing southern beeches (Nothofagus spp.) with different adaptive abilities. *Tree Genetics & Genomes,* **8(4)**, 659-673.

Sommer, J.H., Kreft, H., Kier, G., Jetz, W., Mutke, J., and Barthlott, W., 2010: Projected impacts of climate change on regional capacities for global plant species richness. *Proceedings of the Royal Society B-Biological Sciences,* **277(1692)**, 2271-2280.

Sovacool, B.K., 2009: Contextualizing avian mortality: A preliminary appraisal of bird and bat fatalities from wind, fossil-fuel, and nuclear electricity. *Energy Policy,* **32(6)**, 2241-2248.

Sowerby, A., Emmett, B.A., Tietema, A., and Beier, C., 2008: Contrasting effects of repeated summer drought on soil carbon efflux in hydric and mesic heathland soils. *Global Change Biology,* **14(10)**, 2388-2404.

Sowerby, A., Emmett, B.A., Williams, D., Beier, C., and Evans, C.D., 2010: The response of dissolved organic carbon (DOC) and the ecosystem carbon balance to experimental drought in a temperate shrubland. *European Journal of Soil Science,* **61(5)**, 697-709.

Stahlschmidt, Z.R., DeNardo, D.F., Holland, J.N., Kotler, B.P., and Kruse-Peeples, M., 2011: Tolerance mechanisms in North American deserts: Biological and societal approaches to climate change. *Journal of Arid Environments,* **75(8)**, 681-687.

Staver, A.C., Archibald, S., and Levin, S.A., 2011: The Global Extent and Determinants of Savanna and Forest as Alternative Biome States. *Science,* **334(6053)**, 230-232.

Steenberg, J.W.N., Duinker, P.N., and Bush, P.G., 2011: Exploring adaptation to climate change in the forests of central Nova Scotia, Canada. *Forest Ecology and Management,* **262(12)**, 2316-2327.

Steffen, W., Persson, A., Deutsch, L., Zalasiewicz, J., Williams, M., Richardson, K., Crumley, C., Crutzen, P., Folke, C., Gordon, L., Molina, M., Ramanathan, V., Rockstrom, J., Scheffer, M., Schellnhuber, H.J., and Svedin, U., 2011: The Anthropocene: From Global Change to Planetary Stewardship. *Ambio,* **40(7)**, 739-761.

Steffensen, J.P., Andersen, K.K., Bigler, M., Clausen, H.B., Dahl-Jensen, D., Fischer, H., Goto-Azuma, K., Hansson, M., Johnsen, S.J., Jouzel, J., Masson-Delmotte, V., Popp, T., Rasmussen, S.O., Rothlisberger, R., Ruth, U., Stauffer, B., Siggaard-Andersen, M.L., Sveinbjornsdottir, A.E., Svensson, A., and White, J.W.C., 2008: High-resolution Greenland Ice Core data show abrupt climate change happens in few years. *Science,* **321(5889)**, 680-684.

Stevens, C.J., Dupre, C., Dorland, E., Gaudnik, C., Gowing, D.J.G., Bleeker, A., Diekmann, M., Alard, D., Bobbink, R., Fowler, D., Corcket, E., Mountford, J.O., Vandvik, V., Aarrestad, P.A., Muller, S., and Dise, N.B., 2010a: Nitrogen deposition threatens species richness of grasslands across Europe. *Environmental Pollution,* **158(9)**, 2940-2945.

Stevens, V.M., Turlure, C., and Baguette, M., 2010b: A meta-analysis of dispersal in butterflies. *Biological Reviews,* **85(3)**, 625-642.

Stewart, I.T., 2009: Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrological Processes,* **23(1)**, 78-94.

Stewart, I.T., Cayan, D.R., and Dettinger, M.D., 2005: Changes toward earlier streamflow timing across western North America. *Journal of Climate,* **18(8)**, 1136-1155.

Stewart, J.B., 1988: Modelling surface conductance of pine forest.Agricultural and Forest Meteorology. *Agricultural and Forest Meteorology* **43**, 19-35.

Stinson, G., Kurz, W.A., Smyth, C.E., Neilson, E.T., Dymond, C.C., Metsaranta, J.M., Goisvenue, C., Rampley, C.J., Li, Q., White, T.M., and Blain, D., 2011: An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. *Global Change Biology*, **17(6)**, 2227-2244.

Stow, D., Petersen, A., Hope, A., Engstrom, R., and Coulter, L., 2007: Greenness trends of Arctic tundra vegetation in the 1990s: comparison of two NDVI data sets from NOAA AVHRR systems. *International Journal of Remote Sensing*, **28**, 4807-4822.

Strayer, D.L., and Dudgeon, D., 2010: Freshwater biodiversity conservation: recent progress and future challenges. *Journal of the North American Benthological Society*, **29(1)**, 344-358.

Sturm, M., Schimel, J., Michaelson, G., Welker, J.M., Oberbauer, S.F., Liston, G.E., Fahnestock, J., and Romanovsky, V.E., 2005: Winter biological processes could help convert arctic tundra to shrubland. *Bioscience*, **55(1)**, 17-26.

Suarez, F., Binkley, D., Kaye, M.W., and Stottlemyer, R., 1999: Expansion of forest stands into tundra in the Noatak National Preserve, northwest Alaska. *Ecoscience*, **6(3)**, 465-470.

SuFen, W., ShaoZhong, K., Lu, Z., and FuSheng, L., 2008: Modelling hydrological response to different land-use and climate change scenarios in the Zamu River basin of northwest China. *Hydrological Processes*, **22(14)**, 2502-2510.

Suggitt, A.J., Stefanescu, C., Paramo, F., Oliver, T., Anderson, B.J., Hill, J.K., Roy, D.B., Brereton, T., and Thomas, C.D., 2012: Habitat associations of species show consistent but weak responses to climate. *Biology Letters*, **8(4)**, 590-593.

Sunday, J.M., Bates, A.E., and Dulvy, N.K., 2012: Thermal tolerance and the global redistribution of animals. *Nature Climate Change*, **2(9)**, 686-690.

Sunley, R.J., Atkinson, C.J., and Jones, H.G., 2006: Chill unit models and recent changes in the occurrence of Winter chill and Spring frost in the United Kingdom. *Journal of Horticultural Science & Biotechnology*, **81(6)**, 949-958.

Suttle, K.B., Thomsen, M.A., and Power, M.E., 2007: Species Interactions Reverse Grassland Responses to Changing Climate. *Science*, **315(5812)**, 640-642.

Sutton, M.A., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Grennfelt, P., van Grinsven, H., and Grizzetti, B., 2011: The European Nitrogen Assessment - Sources, Effects and Policy Perspectives. In. Cambridge University Press, pp. 664.

Swab, R.M., Regan, H.M., Keith, D.A., Regan, T.J., and Ooi, M.K.J., 2012: Niche models tell half the story: spatial context and life-history traits influence species responses to global change. *Journal of Biogeography*, **39(7)**, 1266-1277.

Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R., Day, J., Vorosmarty, C., Saito, Y., Giosan, L., and Nicholls, R.J., 2009: Sinking deltas due to human activities. *Nature Geoscience*, **2(10)**, 681-686.

Szeicz, J.M., and Macdonald, G.M., 1995: Recent White Spruce Dynamics at the Subarctic Alpine Treeline of North-Western Canada. *Journal of Ecology*, **83(5)**, 873-885.

Szlavik, J., and Csete, M., 2012: Climate and Energy Policy in Hungary. *Energies*, **5(2)**, 494-517.

Tarnocai, C., Canadell, J.G., Schuur, E.A.G., Kuhry, P., Mazhitova, G., and Zimov, S., 2009: Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles*, **23**.

Taylor, S., Kumar, L., Reid, N., and Kriticos, D.J., 2012: Climate Change and the Potential Distribution of an Invasive Shrub, Lantana camara L. *PLoS One*, **7(4)**.

Tchebakova, N.M., Parfenova, E., and Soja, A.J., 2009: The effects of climate, permafrost and fire on vegetation change in Siberia in a changing climate. *Environmental Research Letters*, **4(4)**.

TEEB, 2009: *TEEB Climate Issues Update.* September 2009, 32-32 pp.

Teixiera, E., Fischer, G., van Veldhuizen, H., van Dingenen, R., Dentener, F., Mills, G., Walter, C., and Ewert, F., 2011: Limited potential of crop management for mitigating surface impacts on global food supply. *Atmospheric Environment*, **45(15)**, 2569-2576.

ten Brink, P., Chiabai, A., Rayment, M., Braeuer, N., Peralta Bezerra, N., Kettunen, M., and Braat, L., 2008: The cost of policy inaction - in monetary terms. In *The cost of policy inaction. The case of not meeting the 2010 biodiversity target* [L. L. Braat & P. ten Brink (eds.)]. Alterra, Wageningen UR; Institute for European Environmental Policy, Wageningen, pp. 119-169.

Thackeray, S.J., Sparks, T.H., Frederiksen, M., Burthe, S., Bacon, P.J., Bell, J.R., Botham, M.S., Brereton, T.M., Bright, P.W., Carvalho, L., Clutton-Brock, T., Dawson, A., Edwards, M., Jones, I.D., Jones, J.T., Leech, D.I., Roy, D.B., Scott, W.A., Smith, M., Smithers, R.J., Winfield, I.J., and Wanless, S., 2010: Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. *Global Change Biology*, **16(12)**, 3304-3313.

Thaxter, C.B., Joys, A.C., Gregory, R.D., Baillie, S.R., and Noble, D.G., 2010: Hypotheses to explain patterns of population change among breeding bird species in England. *Biological Conservation*, **143(9)**, 2006-2019.

The Royal Society, 2008: *Ground-level ozone in the 21st century: future trends, impacts and policy implications.* London, 132 pp.

Thomas, C.D., Franco, A.M.A., and Hill, J.K., 2006: Range retractions and extinction in the face of climate warming. *Trends in Ecology & Evolution,* **21(8)**, 415-416.

Thompson, P.L., Jacques, M.C., and Vinebrooke, R.D., 2008: Impacts of climate warming and nitrogen deposition on alpine plankton in lake and pond habitats: an in vitro experiment. *Arctic Antarctic and Alpine Research,* **40(1)**, 192-198.

Thonicke, K., Venevsky, S., Sitch, S., and Cramer, W., 2008: The role of fire disturbance for global vegetation dynamics: coupling fire into a Dynamic Global Vegetation Model. *Global Ecology and Biogeography,* **10**, 661-667.

Thornton, P.K., van de Steeg, J., Notenbaert, A., and Herrero, M., 2009: The impacts of climate change on livestock and livestock systems in developing countries: A review of what we know and what we need to know. *Agricultural Systems,* **101(3)**, 113-127.

Thorup, K., Tottrup, A.P., and Rahbek, C., 2007: Patterns of phenological changes in migratory birds. *Oecologia,* **151(4)**, 697-703.

Throop, H.L., and Archer, S.R., 2008: Shrub (Prosopis velutina) encroachment in a semidesert grassland: spatial–temporal changes in soil organic carbon and nitrogen pools. *Global Change Biology,* **14(10)**, 2420-2431.

Thuiller, W., Lavergne, S., Roquet, C., Boulangeat, I., Lafourcade, B., and Araujo, M.B., 2011: Consequences of climate change on the tree of life in Europe. *Nature,* **470(7335)**, 531-534.

Thuiller, W., Lavorel, S., Araujo, M.B., Sykes, M.T., and Prentice, I.C., 2005: Climate change threats to plant diversity in Europe. *Proceedings of the National Academy of Sciences of the United States of America,* **102(23)**, 8245-8250.

Tilman, D., Balzer, C., Hill, J., and Befort, B.L., 2011: Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America,* **108(50)**, 20260-20264.

Tingley, M.W., Koo, M.S., Moritz, C., Rush, A.C., and Beissinger, S.R., 2012: The push and pull of climate change causes heterogeneous shifts in avian elevational ranges. *Global Change Biology,* **18(11)**, 3279-3290.

Tisseuil, C., Vrac, M., Grenouillet, G., Wade, A.J., Gevrey, M., Oberdorff, T., Grodwohl, J.B., and Lek, S., 2012: Strengthening the link between climate, hydrological and species distribution modeling to assess the impacts of climate change on freshwater biodiversity. *Science of the Total Environment,* **424**, 193-201.

Tng, D.Y.P., Murphy, B.P., Weber, E., Sanders, G., Williamson, G.J., Kemp, J., and Bowman, D.M.J.S., 2012: Humid tropical rain forest has expanded into eucalypt forest and savanna over the last 50 years. *Ecology and Evolution,* **2(1)**, 34-45.

Tockner, K., Bunn, S.E., Gordon, C., Naiman, R.J., Quinn, G.P., and Stanford, J.A., 2008: Floodplains: Critically threatened ecosystems. In *Aquatic ecosystems. Trends and Global Prospects.* [N. V. C. Polunin (ed.)]. Cambridge Press, Cambridge, pp. 45-61.

Tol, R.S.J., 2008: The Social Cost of Carbon: Trends, Outliers and Catastrophes. *Economics: The Open-Access, Open Assessment E-Journal,* **2(2008-25)**.

Tomppo, E., Gschwantner, T., Lawrence, M., and McRoberts, R.E. (eds.), 2010: *National Forest Inventories - Pathways for common reporting*. Springer, New York, pp. 612.

Traill, L.W., Bradshaw, C.J.A., Delean, S., and Brook, B.W., 2010: Wetland conservation and sustainable use under global change: a tropical Australian case study using magpie geese. *Ecography,* **33(5)**, 818-825.

Trathan, P.N., Fretwell, P.T., and Stonehouse, B., 2011: First Recorded Loss of an Emperor Penguin Colony in the Recent Period of Antarctic Regional Warming: Implications for Other Colonies. *PLoS One,* **6(2)**, 1-11.

Trivedi, M.R., Berry, P.M., Morecroft, M.D., and Dawson, T.P., 2008: Spatial scale affects bioclimate model projections of climate change impacts on mountain plants. *Global Change Biology,* **14(5)**, 1089-1103.

Tseng, W.C., and Chen, C.C., 2008: Valuing the potential economic impact of climate change on the Taiwan trout. *Ecological Economics,* **65(2)**, 282-291.

Turetsky, M.R., Kane, E.S., Harden, J.W., Ottmar, R.D., Manies, K.L., Hoy, E., and Kasischke, E.S., 2011: Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. *Nature Geosci,* **4(1)**, 27-31.

Tylianakis, J.M., Didham, R.K., Bascompte, J., and Wardle, D.A., 2008: Global change and species interactions in terrestrial ecosystems. *Ecology Letters,* **11(12)**, 1351-1363.

Uhl, C., and Kauffman, J.B., 1990: Deforestation, fire susceptibility and potential tree responses to fire in the eastern Amazon. *Ecology,* **71(2)**, 437-449.

United Nations, Department of Economic and Social Affairs, and Population Division, 2012: *World Urbanization Prospects: The 2011 Revision.* 318 pp.

Urban, M.C., Leibold, M.A., Amarasekare, P., De Meester, L., Gomulkiewicz, R., Hochberg, M.E., Klausmeier, C.A., Loeuille, N., de Mazancourt, C., Norberg, J., Pantel, J.H., Strauss, S.Y., Vellend, M., and Wade, M.J., 2008: The evolutionary ecology of metacommunities. *Trends in Ecology & Evolution,* **23(6)**, 311-317.

Urban, M.C., Tewksbury, J.J., and Sheldon, K.S., 2012: On a collision course: competition and dispersal differences create no-analogue communities and cause extinctions during climate change. *Proceedings of the Royal Society B: Biological Sciences,* **279(1735)**, 2072-2080.

Uys, R.G., Bond, J.W., and Everson, T.M., 2004: The effect of different fire regimes on plant diversity southern African grasslands. *Biological Conservation,* **118(4)**, 489-499.

Valdes, P., 2011: Built for stability. *Nature Geoscience,* **4(7)**, 414-416.

van Asch, M., Salis, L., Holleman, L.J.M., van Lith, B., and Visser, M.E., 2012: Evolutionary response of the egg hatching date of a herbivorous insect under climate change. *Nature Climate Change,* **advance online publication**.

van Asch, M., Tienderen, P.H., Holleman, L.J.M., and Visser, M.E., 2007: Predicting adaptation of phenology in response to climate change, an insect herbivore example. *Global Change Biology,* **13(8)**, 1596-1604.

van Asch, M., and Visser, M.E., 2007: Phenology of Forest Caterpillars and Their Host Trees: The Importance of Synchrony. *Annual Review of Entomology,* **52**, 37-55.

Van Auken, O.W., 2009: Causes and consequences of woody plant encroachment into western North American grasslands. *Journal of Environmental Management,* **90(10)**, 2931-2942.

van der Linde, J.A., Six, D.L., Wingfield, M.J., and Roux, J., 2011: Lasiodiplodia species associated with dying Euphorbia ingens in South Africa. *Southern Forests: a Journal of Forest Science,* **73(3-4)**, 165-173.

van der Molen, M.K., van den Hurk, B.J.J.M., and Hazeleger, W., 2011: A dampened land use change climate response towards the tropics. *Climate Dynamics,* **37(9-10)**, 2035-2043.

van der Werf, G.R., Randerson, J.T., Giglio, L., Collatz, G.J., Mu, M., Kasibhatla, P.S., Morton, D.C., DeFries, R.S., Jin, Y., and van Leeuwen, T.T., 2010: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). *Atmos. Chem. Phys,* **223**, 11-707.

Van Herk, I.G., Gower, S.T., Bronson, D.R., and Tanner, M.S., 2011: Effects of climate warming on canopy water dynamics of a boreal black spruce plantation. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere,* **41(2)**, 217-227.

van Kleunen, M., Weber, E., and Fischer, M., 2010: A meta-analysis of trait differences between invasive and non-invasive plant species. *Ecology Letters,* **13(2)**, 235-245.

van Mantgem, P.J., Stephenson, N.L., Byrne, J.C., Daniels, L.D., Franklin, J.F., Fule, P.Z., Harmon, M.E., Larson, A.J., Smith, J.M., Taylor, A.H., and Veblen, T.T., 2009: Widespread Increase of Tree Mortality Rates in the Western United States. *Science,* **323(5913)**, 521-524.

van Vliet, M.T.H., Ludwig, F., Zwolsman, J.J.G., Weedon, G.P., and Kabat, P., 2011: Global river temperatures and sensitivity to atmospheric warming and changes in river flow. *Water Resources Research,* **47(W02544)**, 1-19.

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Nakicenovic, N., Smith, S.J., and Rose, S.K., 2011: The representative concentration pathways: an overview. *Climatic Change,* **109**, 5–31.

van Wilgen, B.W., and Richardson, D.M., 2012: Three centuries of managing introduced conifers in South Africa: Benefits, impacts, changing perceptions and conflict resolution. *Journal of Environmental Management,* **106**, 56-68.

Veldman, J.W., and Putz, F.E., 2011: Grass-dominated vegetation, not species-diverse natural savanna, replaces degraded tropical forests on the southern edge of the Amazon Basin. *Biological Conservation,* **144(5)**, 1419-1429.

Vennetier, M., and Ripert, C., 2010: Climate change impact on vegetation: lessons from an exceptionally hot and dry decade in south-eastern France. *Climate change and variability*.

Verburg, P., Hecky, R.E., and Kling, H., 2003: Ecological consequences of a century of warming in Lake Tanganyika. *Science*, **301(5632)**, 505-507.

Viglizzo, E.F., Frank, F.C., Carreno, L.V., Jobbagy, E.G., Pereyra, H., Clatt, J., Pincen, D., and Ricard, M.F., 2011: Ecological and environmental footprint of 50 years of agricultural expansion in Argentina. *Global Change Biology*, **17(2)**, 959-973.

Vilà-Cabrera, A., Martínez-Vilalta, J., Galiano, L., and Retana, J., 2012: Patterns of Forest Decline and Regeneration Across Scots Pine Populations. *Ecosystems*, 1-13.

Viles, H.A., and Cutler, N.A., 2012: Global environmental change and the biology of heritage structures. *Global Change Biology*, **online early**.

Vinukollu, R.K., Meynadier, R., Sheffield, J., and Wood, E.F., 2011: Multi-model, multi-sensor estimates of global evapotranspiration: climatology, uncertainties and trends. *Hydrol. Process.*, **5**, 3993–4010.

Visser, M.E., and Both, C., 2005: Shifts in phenology due to global climate change: the need for a yardstick. *Proceedings of the Royal Society of London Series B - Biological Sciences*, **272(1665)**, 2561-2569.

Visser, M.E., Holleman, L.J.M., and Caro, S.P., 2009: Temperature has a causal effect on avian timing of reproduction. *Proceedings of the Royal Society B: Biological Sciences*, **276(1665)**, 2323-2331.

Vitt, P., Havens, K., and Hoegh-Guldberg, O., 2009: Assisted migration: part of an integrated conservation strategy. *Trends in Ecology & Evolution*, **24(9)**, 473-474.

Vitt, P., Havens, K., Kramer, A.T., Sollenberger, D., and Yates, E., 2010: Assisted migration of plants: Changes in latitudes, changes in attitudes. *Biological Conservation*, **143(1)**, 18-27.

Vittoz, P., Randin, C., Dutoit, A., Bonnet, F., and Hegg, O., 2009: Low impact of climate change on subalpine grasslands in the Swiss Northern Alps. *Global Change Biology*, **15(1)**, 209-220.

Vohland, K., and Barry, B., 2009: A review of in situ rainwater harvesting (RWH) practices modifying landscape functions in African drylands. *Agriculture Ecosystems & Environment*, **131(3-4)**, 119-127.

Vongraven, D., and Richardson, E., 2011: Biodiversity - Status and Trends of Polar Bears. *Arctic Report Card: Update for 2011*, 2012, from www.arctic.noaa.gov/reportcard/biodiv_polar_bears.html.

Vörösmarty, C.J., Green, P., Salisbury, J., and Lammers, R.B., 2000: Global water resources: Vulnerability from climate change and population growth. *Science*, **289(5477)**, 284-288.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R., and Davies, P.M., 2010: Global threats to human water security and river biodiversity (vol 467, pg 555, 2010). *Nature*, **468(7321)**, 334-334.

Vredenburg, V.T., Knapp, R.A., Tunstall, T.S., and Briggs, C.J., 2010: Dynamics of an emerging disease drive large-scale amphibian population extinctions. *Proceedings of the National Academy of Sciences of the United States of America*, **107(21)**, 9689-9694.

Wagner, C., and Adrian, R., 2009: Cyanobacteria dominance: Quantifying the effects of climate change. *Limnology and Oceanography*, **54(6)**, 2460-2468.

Wake, D.B., 2012: Facing Extinction in Real Time. *Science*, **335(6072)**, 1052-1053.

Walker, B., Holling, C.S., Carpenter, S.R., and Kinzig, A., 2004: Resilience, adaptability and transformability in socialâ€“ecological systems.9(2): 5. *Ecology and Society*, **9(2)**, 5.

Walker, B.H., and Langridge, J.L., 1997: Predicting savanna vegetation structure on the basis of plant available moisture (PAM) and plant available nutrients (PAN): A case study from Australia. *Journal of Biogeography*, **24**, 813-825.

Walker, B.H., and Salt, D., 2006: *Resilience Thinking: Sustaining Ecosystems And People In A Changing World*. Island Press, Washington, DC, 174 pp.

Walker, D.A., Epstein, H.E., Raynolds, M.K., Kuss, P., Kopecky, M.A., Frost, G.V., Daniels, F.J.A., Leibman, M.O., Moskalenko, N.G., Matyshak, G.V., Khitun, O.V., Khomutov, A.V., Forbes, B.C., Bhatt, U.S., Kade, A.N., Vonlanthen, C.M., and Tichy, L., 2012: Environment, vegetation and greenness (NDVI) along the North America and Eurasia Arctic transects. *Environmental Research Letters*, **7(1)**.

Walker, M.W.C., Hollister RD, Henry GHR, Ahlquist LE, Alatalo JM, Bret-Harte MS, Calef MP, Callaghan TV, Carroll AB, Epstein HE, Jonsdottir IS, Klein JA, Magnusson B, Molau U, Oberbauer SF, Rewa SP, Robinson CH, Shaver GR, Suding KN, Thompson CC, Tolvanen A, Totland O, Turner PL, Tweedie CE, Webber PJ, Wookey PA, 2006: Plant community responses to experimental warming across the tundra biome. *Proceedings of the National Academy of Sciences of the United States of America*, **103(5)**, 1342–1346.

Walter, J., Grant, K., Beierkuhnlein, C., Kreyling, J., Weber, M., and Jentsch, A., 2012: Increased rainfall variability reduces biomass and forage quality of temperate grassland largely independent of mowing frequency. *Agriculture Ecosystems & Environment*, **148**, 1-10.

Walters, R.J., Blanckenhorn, W.U., and Berger, D., 2012: Forecasting extinction risk of ectotherms under climate warming: an evolutionary perspective. *Functional Ecology*, **26(6)**, 1324-1338.

Walther, G.-R., Berger, S., and Sykes, M.T., 2005: An ecological 'footprint' of climate change. *Proceedings of the Royal Society B: Biological Sciences*, **272(1571)**, 1427-1432.

Walther, G.-R., Roques, A., Hulme, P.E., Sykes, M.T., Pysek, P., Kuehn, I., Zobel, M., Bacher, S., Botta-Dukat, Z., Bugmann, H., Czucz, B., Dauber, J., Hickler, T., Jarosik, V., Kenis, M., Klotz, S., Minchin, D., Moora, M., Nentwig, W., Ott, J., Panov, V.E., Reineking, B., Robinet, C., Semenchenko, V., Solarz, W., Thuiller, W., Vila, M., Vohland, K., and Settele, J., 2009: Alien species in a warmer world: risks and opportunities. *Trends in Ecology & Evolution*, **24(12)**, 686-693.

Wang, B., Huang, J., Yang, X., Zhang, B., and Liu, M., 2010a: Estimation of biomass, net primary production and net ecosystem production of China's forests based on the 1999–2003 National Forest Inventory. *Scandinavian Journal of Forest Research*, **25(6)**, 544-553.

Wang, K., Dickinson, E.D., Wild, M., and Liang, S., 2010b: Evidence for decadal variation in global terrestrial evapotranspiration between 1982 and 2002. *Journal of Geophysical Research*, **115(D20133)**.

Ward, D., 2005: Do we understand the causes of bush encroachment in African savannas? *African Journal of Range and Forage Science*, **22(2)**, 101-105.

Wardle, P., and Coleman, M.C., 1992: Evidence for rising upper limits of four native New Zealand forest trees. *New Zealand Journal of Botany*, **30(3)**, 303-314.

Warren, R., Price, J., Fischlin, A., Santos, S.D., and Midgley, G., 2011: Increasing impacts of climate change upon ecosystems with increasing global mean temperature rise. *Climatic Change*, **106(2)**, 141-177.

Warszawski, L., Friend, A., Ostberg, S., Frieler, K., Lucht, W., Schaphoff, S., and Beerling, D., Risk of ecosystem shift under climate change, a multi-model analysis. *Proceeding of the National Academy of Science*, submitted.

Watkiss, P., and Downing, T., 2008: The social cost of carbon: Valuation estimates and their use in UK policy. *Integrated Assessment*, **8(1)**, 85-105.

Watrin, J., Lezine, A.M., and Hely, C., 2009: Plant migration and plant communities at the time of the "green Sahara". *Comptes Rendus Geoscience*, **341(8-9)**, 656-670.

Wearn, O.R., Reuman, D.C., and Ewers, R.M., 2012: Extinction Debt and Windows of Conservation Opportunity in the Brazilian Amazon. *Science*, **337(6091)**, 228-232.

Webb, B.W., and Nobilis, F., 2007: Long-term changes in river temperature and the influence of climatic and hydrological factors. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques*, **52(1)**, 74-85.

Welp, L.R., Randerson, J.T., and Liu, H.P., 2007: The sensitivity of carbon fluxes to spring warming and summer drought depends on plant functional type in boreal forest ecosystems. *Agricultural and Forest Meteorology*, **147(3-4)**, 172-185.

Weng, E.S., and Zhou, G.S., 2006: Modeling distribution changes of vegetation in China under future climate change. *Environmental Modeling & Assessment*, **11(1)**, 45-58.

West, J., Julius, S.H., Kareiva, P., Enquist, C., Lawler, J.J., Petersen, B., Johnson, A.E., and Shaw, M.R., 2009: U.S. Natural Resources and Climate Change: Concepts and Approaches for Management Adaptation. *Environmental Management*, **44(6)**, 1001-1021.

West, J.S., Townsend, J.A., Stevens, M., and Fitt, B.D.L., 2012: Comparative biology of different plant pathogens to estimate effects of climate change on crop diseases in Europe. *European Journal of Plant Pathology*, **133(1)**, 315-331.

Westerling, A., Hidalgo, H., Cayan, D., and Swetnam, T., 2006: Warming and earlier spring increase western US forest wildfire activity. *Science*, **313(5887)**, 940-943.

Westerling, A.L., Turner, M.G., Smithwick, E.A.H., Romme, W.H., and Ryan, M.G., 2011: Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. *Proceedings of the National Academy of Sciences of the USA 108: 13 165-13 170*, **108(13)**, 165-113 170.

Westley, F., Olsson, P., Folke, C., Homer-Dixon, T., Vredenburg, H., Loorbach, D., Thompson, J., Nilsson, M., Lambin, E., Sendzimir, J., Banerjee, B., Galaz, V., and van der Leeuw, S., 2011: Tipping Toward Sustainability: Emerging Pathways of Transformation. *Ambio*, **40(7)**, 762-780.

White, M.A., de Beurs, K.M., Didan, K., Inouye, D.W., Richardson, A.D., Jensen, O.P., O'Keefe, J., Zhang, G., Nemani, R.R., van Leeuwen, W.J.D., Brown, J.F., de Wit, A., Schaepman, M., Lin, X.M., Dettinger, M., Bailey, A.S., Kimball, J., Schwartz, M.D., Baldocchi, D.D., Lee, J.T., and Lauenroth, W.K., 2009: Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote sensing for 1982-2006. *Global Change Biology,* **15(10)**, 2335-2359.

Wickham, J.D., Wade, T.G., and Riitters, K.H., 2012: Empirical analysis of the influence of forest extent on annual and seasonal surface temperatures for the continental United States. *Global Ecology and Biogeography,* n/a-n/a.

Wiedner, C., Rucker, J., Bruggemann, R., and Nixdorf, B., 2007: Climate change affects timing and size of populations of an invasive cyanobacterium in temperate regions. *Oecologia,* **152(3)**, 473-484.

Wiegand, K., Ward, D., and Saltz, D., 2005: Multi-scale patterns and bush encroachment in an arid savanna with a shallow soil layer. *Journal of Vegetation Science,* **16(3)**, 311-320.

Wiens, J.A., Seavy, N.E., and Jongsomjit, D., 2011: Protected areas in climate space: What will the future bring? *Biological Conservation,* **144(8)**, 2119-2125.

Wigley, B.J., Bond, W.J., and Hoffman, M.T., 2009: Bush encroachment under three contrasting land-use practices in a mesic South African savanna. *African Journal of Ecology,* **47(s1)**, 62-70.

Wiley, M.J., Hyndman, D.W., Pijanowski, B.C., Kendall, A.D., Riseng, C., Rutherford, E.S., Cheng, S.T., Carlson, M.L., Tyler, J.A., Stevenson, R.J., Steen, P.J., Richards, P.L., Seelbach, P.W., Koches, J.M., and Rediske, R.R., 2010: A multi-modeling approach to evaluating climate and land use change impacts in a Great Lakes River Basin. *Hydrobiologia,* **657(1)**, 243-262.

Wilkinson, S., and Davies, W.J., 2010: Drought, ozone, ABA and ethylene: new insights from cell to plant to community. *Plant Cell and Environment,* **33(4)**, 510-525.

Williams, A.L., Wills, K.E., Janes, J.K., Schoor, J.K.V., Newton, P.C.D., and Hovenden, M.J., 2007a: Warming and free-air CO2 enrichment alter demographics in four co-occurring grassland species. *New Phytologist,* **176(2)**, 365-374.

Williams, A.P., Allen, C.D., Macalady, A.K., Griffin, D., Woodhouse, C.A., Meko, D.M., Swetnam, T.W., Rauscher, S.A., Seager, R., Grissino-Mayer, H.D., Dean, J.S., Cook, E.R., Gangodagamage, C., Cai, M., and McDowell, N.G., 2012: Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Clim. Change,* **advance online publication**.

Williams, A.P., Allen, C.D., Millar, C.I., Swetnam, T.W., Michaelsen, J., Still, C.J., and Leavitt, S.W., 2010a: Forest responses to increasing aridity and warmth in the southwestern United States. *Proceedings of the National Academy of Sciences of the United States of America,* **107(50)**, 21289-21294.

Williams, J.W., Blois, J.L., and Shuman, B.N., 2011: Extrinsic and intrinsic forcing of abrupt ecological change: case studies from the late Quaternary. *Journal of Ecology,* **99(3)**, 664-677.

Williams, J.W., and Jackson, S.T., 2007: Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and the Environment,* **5(9)**, 475-482.

Williams, J.W., Jackson, S.T., and Kutzbacht, J.E., 2007b: Projected distributions of novel and disappearing climates by 2100 AD. *Proceedings of the National Academy of Sciences of the United States of America,* **104(14)**, 5738-5742.

Williams, J.W., Shuman, B., and Bartlein, P.J., 2009: Rapid responses of the prairie-forest ecotone to early Holocene aridity in mid-continental North America. *Global and Planetary Change,* **66(3-4)**, 195-207.

Williams, J.W., Shuman, B., Bartlein, P.J., Diffenbaugh, N.S., and Webb, T., 2010b: Rapid, time-transgressive, and variable responses to early Holocene midcontinental drying in North America. *Geology,* **38(2)**, 135-138.

Willis, C.G., Ruhfel, B.R., Primack, R.B., Miller-Rushing, A.J., Losos, J.B., and Davis, C.C., 2010a: Favorable Climate Change Response Explains Non-Native Species' Success in Thoreau's Woods. *PLoS One,* **5(1)**, 1-5.

Willis, C.K.R., Barclay, R.M.R., Boyles, J.G., Brigham, R.M., Brack Jr, V., Waldien, D.L., and Reichard, J., 2010b: Bats are not birds and other problems with Sovacool's (2009) analysis of animal fatalities due to electricity generation. *Energy Policy,* **38**, 2067-2069.

Willis, K.J., Bennett, K.D., Bhagwat, S.A., and Birks, H.J.B., 2010c: 4 °C and beyond: what did this mean for biodiversity in the past? *Systematics and Biodiversity,* **8(1)**, 3-9.

Willis, K.J., and Bhagwat, S.A., 2009: Biodiversity and Climate Change. *Science,* **326(5954)**, 806-807.

Willis, K.J., and MacDonald, G.M., 2011: Long-Term Ecological Records and Their Relevance to Climate Change Predictions for a Warmer World. In *Annual Review of Ecology, Evolution, and Systematics, Vol 42* [D. J. Futuyma, H. B. Shaffer & D. Simberloff (eds.)]. pp. 267-287.

Wilson, R., D'Arrigo, R., Buckley, B., BÃ¼ntgen, U., Esper, J., Frank, D., Luckman, B., Payette, S., Vose, R., and Youngblut, D., 2007: A matter of divergence: Tracking recent warming at hemispheric scales using tree ring data. *Journal of Geophysical Research - Atmospheres,* **112(D17103)**, 1-17.

Winder, M., Jassby, A.D., and Mac Nally, R., 2011: Synergies between climate anomalies and hydrological modifications facilitate estuarine biotic invasions. *Ecology Letters*, **14(8)**, 749-757.

Winder, M., and Schindler, D.E., 2004: Climatic effects on the phenology of lake processes. *Global Change Biology*, **10(11)**, 1844-1856.

Wing, S.L., Harrington, G.J., Smith, F.A., Bloch, J.I., Boyer, D.M., and Freeman, K.H., 2005: Transient floral change and rapid global warming at the Paleocene-Eocene boundary. *Science*, **310(5750)**, 993-996.

Winter, M., Schweiger, O., Klotz, S., Nentwig, W., Andriopoulos, P., Arianoutsou, M., Basnou, C., Delipetrou, P., Didziulis, V., Hejda, M., Hulme, P.E., Lambdon, P.W., Pergl, J., Pyšek, P., Roy, D.B., and Kühn, I., 2009: Plant extinctions and introductions lead to phylogenetic and taxonomic homogenization of the European flora. *Proceedings of the National Academy of Sciences of the United States of America*, **106(51)**, 21721-21725.

Wise, M., Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R., Smith, S.J., Janetos, A., and Edmonds, J., 2009: Implications of Limiting CO2 Concentrations for Land Use and Energy. *Science*, **324(5931)**, 1183-1186.

Witt, G.B., Harrington, R.A., and Page, M.J., 2009: Is ‘vegetation thickening’ occurring in Queensland’s mulga lands – a 50-year aerial photographic analysis. . *Australian Journal of Botany*, **57(7)**, 572-582.

Witte, J.C., Douglass, A.R., da Silva, A., Torres, O., Levy, R., and Duncan, B.N., 2011: NASA A-Train and Terra observations of the 2010 Russian wildfires. *Atmospheric Chemistry and Physics*, **11(17)**, 9287-9301.

Wittig, V.E., Ainsworth, E.A., and Long, S.P., 2007: To what extent do current and projected increases in surface ozone affect photosynthesis and stomatal conductance of trees? A meta-analytic review of the last 3 decades of experiments. *Plant, Cell & Environment*, **30(9)**, 1150-1162.

Wittig, V.E., Ainsworth, E.A., Naidu, S.L., Karnosky, D.F., and Long, S.P., 2009: Quantifying the impact of current and future tropospheric ozone on tree biomass, growth physiology and biochemistry. *Global Change Biology*, **15(2)**, 396-424.

Wolken, J.M., Hollingsworth, T.N., Rupp, T.S., Chapin, F.S., Trainor, S.F., Barrett, T.M., Sullivan, P.F., McGuire, A.D., Euskirchen, E.S., Hennon, P.E., Beever, E.A., Conn, J.S., Crone, L.K., D'Amore, D.V., Fresco, N., Hanley, T.A., Kielland, K., Kruse, J.J., Patterson, T., Schuur, E.A.G., Verbyla, D.L., and Yarie, J., 2011: Evidence and implications of recent and projected climate change in Alaska's forest ecosystems. *Ecosphere*, **2(11)**, art124.

Wolkovich, E.M., Cook, B.I., Allen, J.M., Crimmins, T.M., Betancourt, J.L., Travers, S.E., Pau, S., Regetz, J., Davies, T.J., Kraft, N.J.B., Ault, T.R., Bolmgren, K., Mazer, S.J., McCabe, G.J., McGill, B.J., Parmesan, C., Salamin, N., Schwartz, M.D., and Cleland, E.E., 2012: Warming experiments underpredict plant phenological responses to climate change. *Nature*, **advance online publication**, 1-4.

Wood, T.E., Cavaleri, M.A., and Reed, S.C., 2012: Tropical forest carbon balance in a warmer world: a critical review spanning microbial- to ecosystem-scale processes. *Biological Reviews*, **87(4)**, 912-927.

Woodburne, M.O., Gunnell, G.F., and Stucky, R.K., 2009: Climate directly influences Eocene mammal faunal dynamics in North America. *Proceedings of the National Academy of Sciences of the United States of America*, **106(32)**, 13399-13403.

Worrall, J.J., Rehfeldt, G.E., Hamann, A., Hogg, E.H., Marchetti, S.B., Michaelian, M., and Gray, L.K., 2013: Recent declines of Populus tremuloides in North America linked to climate. *Forest Ecology and Management*.

Wu, C.Y., and Chen, J.M., 2013: Diverse responses of vegetation production to interannual summer drought in North America. *International Journal of Applied Earth Observation and Geoinformation*, **21**, 1-6.

Wu, X.B., and Archer, S.R., 2005: Scale-dependent influence of topography-based hydrologic features on patterns of woody plant encroachment in savanna landscapes. *Landscape Ecology*, **20(6)**, 733-742.

Wu, Z., Zhang, H., Krause, C.M., and Cobb, N.S., 2010: Climate change and human activities: a case study in Xinjiang, China. *Climatic Change*, **99(3-4)**, 457-472.

Xenopoulos, M.A., Lodge, D.M., Alcamo, J., Marker, M., Schulze, K., and Van Vuuren, D.P., 2005: Scenarios of freshwater fish extinctions from climate change and water withdrawal. *Global Change Biology*, **11(10)**, 1557-1564.

Xu, L., Myneni, R.B., Chapin III, F.S., Callaghan, T.V., Pinzon, J.E., Tucker, C.J., Zhu, Z., Bi, J., Ciais, P., Tømmervik, H., Euskirchen, E.S., Forbes, B.C., Piao, S.L., Anderson, B.T., Ganguly, S., Nemani, R.R., Goetz, S.J., Beck, P.S.A., Bunn, A.G., Cao, C., and Stroeve, J.C., 2013: Diminished temperature and vegetation seasonality over northern high latitudes. *Nature Climate Change*, in press.

Yi, S.H., Woo, M.K., and Arain, M.A., 2007: Impacts of peat and vegetation on permafrost degradation under climate warming. *Geophysical Research Letters*, **34(16)**.

Yoshikawa, S., and Sanga-Ngoie, K., 2011: Deforestation dynamics in Mato Grosso in the southern Brazilian Amazon using GIS and NOAA/AVHRR data. *International Journal of Remote Sensing,* **32(2)**, 523-544.

Yvon-Durocher, G., Montoya, J.M., Trimmer, M., and Woodward, G., 2011: Warming alters the size spectrum and shifts the distribution of biomass in freshwater ecosystems. *Global Change Biology,* **17(4)**, 1681-1694.

Zavaleta, E.S., Shaw, M.R., Chiariello, N.R., Thomas, B.D., Cleland, E.E., Field, C.B., and Mooney, H.A., 2003a: Grassland responses to three years of elevated temperature, CO(2), precipitation, and N deposition. *Ecological Monographs,* **73(4)**, 585-604.

Zavaleta, E.S., Thomas, B.D., Chiariello, N.R., Asner, G.P., Shaw, M.R., and Field, C.B., 2003b: Plants reverse warming effect on ecosystem water balance. *Proceedings of the National Academy of Sciences of the United States of America,* **100(17)**, 9892-9893.

Zelazowski, P., Malhi, Y., Huntingford, C., Sitch, S., and Fisher, J.B., 2011: Changes in the potential distribution of humid tropical forests on a warmer planet. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* **369(1934)**, 137-160.

Zeng, Z., Piao, S., Lin, X., Yin, G., Peng, S., Ciais, P., and Myneni, R.B., 2012: Global evapotranspiration over the past three decades: estimation based on the water balance equation combined with empirical models. *Environmental Research Letters,* **7**.

Zerebecki, R.A., and Sorte, C.J.B., 2011: Temperature Tolerance and Stress Proteins as Mechanisms of Invasive Species Success. *PLoS One,* **6(4)**, 1-7.

Zhang, H., Li, Y., and Gao, X., 2009: Potential impacts of land-use on climate variability and extremes. *Advances in Atmospheric Sciences,* **26(5)**, 840-854.

Zhang, Y.Y., Fischer, M., Colot, V., and Bossdorf, O., 2013: Epigenetic variation creates potential for evolution of plant phenotypic plasticity. *New Phytologist,* **197(1)**, 314-322.

Zhao, M., and Running, S.W., 2010: Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science,* **329(5994)**, 940-943.

Zhou, G., Peng, C., Li, Y., Liu, S., Zhang, Q., Tang, X., Liu, J., Yan, J., Zhang, D., and Chu, G., 2013: A climate change-induced threat to the ecological resilience of a subtropical monsoon evergreen broad-leaved forest in Southern China. *Global Change Biology,* n/a-n/a.

Zhou, Y.P., Xu, K.M., Sud, Y.C., and Betts, A.K., 2011: Recent trends of the tropical hydrological cycle inferred from Global Precipitation Climatology Project and International Satellite Cloud Climatology Project data. *Journal of Geophysical Research-Atmospheres,* **116(D09101)**.

Zhu, K., Woodall, C.W., and Clark, J.S., 2012: Failure to migrate: lack of tree range expansion in response to climate change. *Global Change Biology,* **18(3)**, 1042-1052.

Zimov, N.S., Zimov, S.A., Zimova, A.E., Zimova, G.M., Chuprynin, V.I., and Chapin, F.S., 2009: Carbon storage in permafrost and soils of the mammoth tundra-steppe biome: Role in the global carbon budget. *Geophysical Research Letters,* **36**.

Zurell, D., Grimm, V., Rossmanith, E., Zbinden, N., Zimmermann, N.E., and Schroder, B., 2012: Uncertainty in predictions of range dynamics: black grouse climbing the Swiss Alps. *Ecography,* **35(7)**, 590-603.

Zyryanova, O.A., V. T. Yaborov, T. I. Tchikhacheva, T. Koike, K. Makoto, Y. Matsuura, F. Satoh, and V. I. Zyryanov, 2007: The structure and biodiversity after fire disturbance in Larix gmelinii (Rupr.) Rupr. Forests. *Northeasten Asia Eurasian Journal of Forest Research,* **10(1)**, 19-29.

Table 4-1: Biome shifts from 1700 to the present from published field research that examined trends over periods > 30 y for biomes in areas where climate (rather than land-use change or other factors) predominantly influenced vegetation, derived from a systematic analysis of published studies (Gonzalez *et al.* (2010). Pre-AR4 publications are included to provide a comprehensive review. Shift type: elevational (E), latitudinal (L), examined but not detected (N). Biomes (and abbreviations), from poles to equator: tundra and alpine (UA), boreal conifer forest (BC), temperate conifer forest (TC), temperate broadleaf forest (TB), temperate shrubland (TS), tropical grassland (RG), tropical woodland (RW). Rate of change in temperature (Temp.) and fractional rate of change in precipitation (Precip.) are derived from linear least squares regression of 1901-2002 data (Mitchell and Jones, 2005; Gonzalez *et al.*, 2010). The table provides general regional climate trends at 50 km spatial resolution because the references do not give uniform site-specific climate data to compare across locations. The regional trends are consistent with local trends reported in each reference. * rate significant at P ≤ 0.05).

	Location	**Reference**	**Plots**	**Time Period**	**Shift type**	**Retracting biome**	**Expanding biome**	**Temp. change (ºC century^{-1})**	**Precip. change (century^{-1})**
1.	Alaska Range, Alaska, USA	Lloyd and Fastie, 2003	18	1800-2000	L	UA	BC	1.1*	0.03
2.	Baltic Coast, Sweden	Walther *et al.*, 2005	7	1944-2003	L	TC	TB	0.6*	0.08
3.	Becca di Viou, Italy	Leonelli *et al.*, 2011	1	1700-2008	E	UA	BC	0.9*	-0.06
4.	Garibaldi, British Columbia, Canada	Brink, 1959	1	1860-1959	E	UA	BC	0.7*	0.16*
5.	Goulet Sector, Québec, Canada	Payette and Filion, 1985	2	1880-1980	E	UA	BC	1.4*	0.19*
6.	Green Mountains, Vermont, USA	Beckage *et al.*, 2008	33	1962-2005	E	BC	TB	1.6*	0.06
7.	Jasper, Alberta, Canada	Luckman and Kavanagh, 2000	1	1700-1994	E	UA	BC	0.6	0.21*
8.	Kenai Mountains, Alaska, USA	Dial *et al.*, 2007	3	1951-1996	E	UA	BC	0.7	0.06
9.	Kluane Range, Yukon, Canada	Danby and Hik, 2007	2	1800-2000	E	UA	BC	0.7	0.05
10.	Low Peninsula, Québec, Canada	Payette and Filion, 1985	1	1750-1980	N	-	-	1.4*	0.19*
11.	Mackenzie Mountains, Northwest Territories, Canada	Szeicz and Macdonald, 1995	13	1700-1990	N	-	-	1.4*	0.03
12.	Montseny Mountains, Catalonia, Spain	Peñuelas and Boada, 2003	50	1945-2001	E	UA	TB	1.2*	-0.03
13.	Napaktok Bay, Labrador, Canada	Payette, 2007	2	1750-2000	L	UA	BC	1.1*	0.05
14.	Noatak, Alaska, USA	Suarez *et al.*, 1999	18	1700-1990	L	UA	BC	0.6	0.19*

	Location	**Reference**	**Plots**	**Time Period**	**Shift type**	**Retracting biome**	**Expanding biome**	**Temp. change (°C century^{-1})**	**Precip. change (century^{-1})**
15.	Putorana Mountains, Russia	Kirdyanov *et al.*, 2012	10	1500-2000	E	UA	BC	0.3	0.10
16.	Rahu Saddle, New Zealand	Cullen *et al.*, 2001	7	1700-2000	N	-	-	0.6*	0.03
17.	Rai-Iz, Urals, Russia	Devi *et al.*, 2008	144	1700-2002	E	UA	BC	0.3	0.35*
18.	Sahel, Sudan, Guinea zones; Senegal	Gonzalez, 2001	135	1945-1993	L	RW	RG	0.4*	-0.48*
19.	Sahel, Burkina Faso, Chad, Mali, Mauritania, Niger	Gonzalez *et al.*, 2012	14	1960-2000	L	RW	RG	-0.01*-to 0.8*	-0.31*-to 0.09
20.	Scandes, Sweden	Kullman and Öberg, 2009	123	1915-2007	E	UA	BC	0.8*	0.25*
21.	Sierra Nevada, California, USA	Millar *et al.*, 2004	10	1880-2002	E	UA	TC	-0.1	0.21*
22.	South Island, New Zealand	Wardle and Coleman, 1992	22	1980-1990	E	TS	TB	0.6*	0.03
23.	Yambarran, Northern Territory, Australia	Sharp and Bowman, 2004	33	1948-2000	N	-	-	-0.06	0.35*

Table 4-2: Summary of drivers and outcomes of land use / cover scenarios associated with Representative Concentration Pathways (Hurtt et al., 2011).

RCP	Key assumptions / drivers	Land use / cover outcomes
8.5-MESSAGE	No climate change mitigation actions; radiative forcing still rising at 2100 Strong increase in agricultural resource use driven by the increasing population (rises to 12 billion people by 2100) Yield improvements and intensification assumed to account for most of production increases	**Increase in cultivated land by about 305 million ha from 2000 to 2100** **Forest cover declines by 450 million ha from 2000 to 2100** **Arable land use in developed countries slightly decreased - all of the net increases occur in developing countries.**
6.0-AIM	Mitigation actions taken late in the century to stabilize radiative forcing at 6 Wm^{-2} after 2100 Population growth and economic growth Increasing food demand drives cropland expansion	**Urban land-use increases** **Cropland area expands** **Grassland area declines** **Total forested area extent remains constant**
4.5-GCM	Mitigation stabilizes radiative forcing at 4.5 Wm–2 before 2100 Assumes that global GHG emissions prices are invoked to limit emissions and therefore radiative forcing. Emissions pricing assumes all carbon emissions charged an equal penalty price, so reductions in land-use change carbon emissions available as mitigation Food demand met through crop yield improvements, dietary shifts, production efficiency and international trade.	**Preservation of large stocks of terrestrial carbon in forests** **Overall expansion in forested area** **Agricultural land declines slightly due to afforestation,**
2.6-IMAGE	Overall trends in land use and land cover mainly determined by demand, trade and production of agricultural products and bio-energy	**Much agriculture relocates from high income to low income regions** **Increase in bio-energy production, new area for bioenergy crops near current agricultural areas.**

Table References Chapter 4 SOD

Beckage, B., Osborne, B., Gavin, D.G., Pucko, C., Siccama, T., and Perkins, T., 2008: A rapid upward shift of a forest ecotone during 40 years of warming in the Green Mountains of Vermont. Proceedings of the National Academy of Sciences of the United States of America, 105(11), 4197-4202.

Brink, V.C., 1959: A Directional Change in the Subalpine Forest-Heath Ecotone in Garibaldi Park, British Columbia. Ecology, 40(1), 10-16.

Cullen, L.E., Stewart, G.H., Duncan, R.P., and Palmer, J.G., 2001: Disturbance and climate warming influences on New Zealand Nothofagus tree-line population dynamics. Journal of Ecology, 89(6), 1061-1071.

Danby, R.K., and Hik, D.S., 2007: Variability, contingency and rapid change in recent subarctic alpine tree line dynamics. Journal of Ecology, 95(2), 352-363.

Devi, N., Hagedorn, F., Moiseev, P., Bugmann, H., Shiyatov, S., Mazepa, V., and Rigling, A., 2008: Expanding forests and changing growth forms of Siberian larch at the Polar Urals treeline during the 20th century. Global Change Biology, 14(7), 1581-1591.

Dial, R.J., Berg, E.E., Timm, K., McMahon, A., and Geck, J., 2007: Changes in the alpine forest-tundra ecotone commensurate with recent warming in southcentral Alaska: Evidence from orthophotos and field plots. J. Geophys. Res., 112(G4), G04015.

Gonzalez, P., 2001: Desertification and a shift of forest species in the West African Sahel. Climate Research, 17(2), 217-228.

Gonzalez, P., Tucker, C.J., and Sy, H., 2012: Tree density and species decline in the African Sahel attributable to climate. Journal of Arid Environments, 78(0), 55-64.

Kirdyanov, A.V., Hagedorn, F., Knorre, A.A., Fedotova, E.V., Vaganov, E.A., Naurzbaev, M.M., Moiseev, P.A., and Rigling, A., 2012: 20th century tree-line advance and vegetation changes along an altitudinal transect in the Putorana Mountains, northern Siberia. Boreas, 41(1), 56-67.

Kullman, L., and Öberg, L., 2009: Post-Little Ice Age tree line rise and climate warming in the Swedish Scandes: a landscape ecological perspective. Journal of Ecology, 97(3), 415-429.

Leonelli, G., Pelfini, M., Morra di Cella, U., and Garavaglia, V., 2011: Climate Warming and the Recent Treeline Shift in the European Alps: The Role of Geomorphological Factors in High-Altitude Sites. AMBIO: A Journal of the Human Environment, 40(3), 264-273.

Lloyd, A.H., and Fastie, C.L., 2003: Recent changes in tree line forest distribution and structure in interior Alaska. Ecoscience, 10, 176-185.

Luckman, B., and Kavanagh, T., 2000: Impact of Climate Fluctuations on Mountain Environments in the Canadian Rockies. AMBIO: A Journal of the Human Environment, 29(7), 371-380.

Millar, C., Westfall, R., Delany, D., King, J., and Graumlich, L., 2004: Response of Subalpine Conifers in the Sierra Nevada, California, U.S.A., to 20th-century Warming and Decadal Climate Variability. Arctic, Antarctic, and Alpine Research, 36(2), 181-200.

Payette, S., 2007: Contrasted dynamics of northern Labrador tree lines caused by climate change and migrational lag. Ecology, 88(3), 770-780.

Payette, S., and Filion, L., 1985: White spruce expansion at the tree line and recent climatic change. Canadian Journal of Forest Research, 15(1), 241-251.

Peñuelas, J., and Boada, M., 2003: A global change-induced biome shift in the Montseny mountains (NE Spain). Global Change Biology, 9(2), 131-140.

Sharp, B.R., and Bowman, D.M.J.S., 2004: Patterns of long-term woody vegetation change in a sandstone-plateau savanna woodland, Northern Territory, Australia. Journal of Tropical Ecology, 20(03), 259-270.

Suarez, F., Binkley, D., Kaye, M.W., and Stottlemyer, R., 1999: Expansion of forest stands into tundra in the Noatak National Preserve, northwest Alaska. Ecoscience, 6(3), 465-470.

Szeicz, J.M., and Macdonald, G.M., 1995: Recent White Spruce Dynamics at the Subarctic Alpine Treeline of North-Western Canada. Journal of Ecology, 83(5), 873-885.

Walther, G.-R., Berger, S., and Sykes, M.T., 2005: An ecological ‘footprint’ of climate change. Proceedings of the Royal Society B: Biological Sciences, 272(1571), 1427-1432.

Wardle, P., and Coleman, M.C., 1992: Evidence for rising upper limits of four native New Zealand forest trees. New Zealand Journal of Botany, 30(3), 303-314.

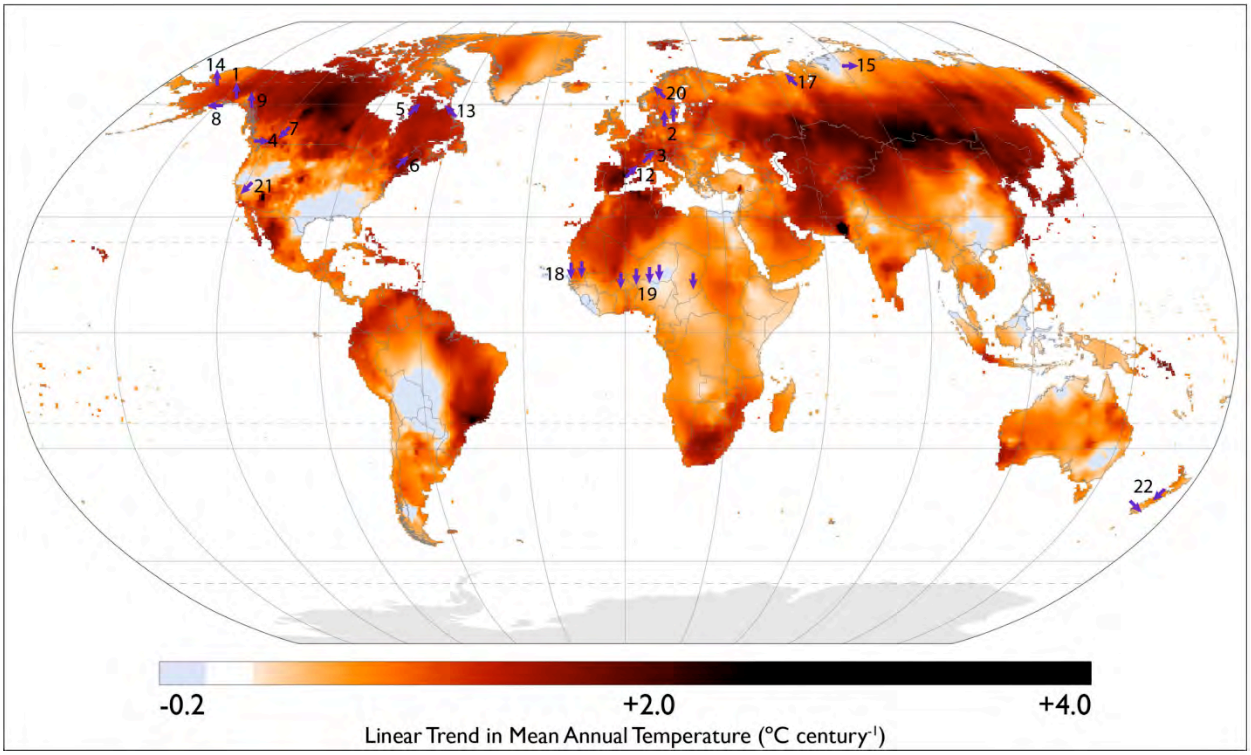


Figure 4-1: Biome shifts in the past.

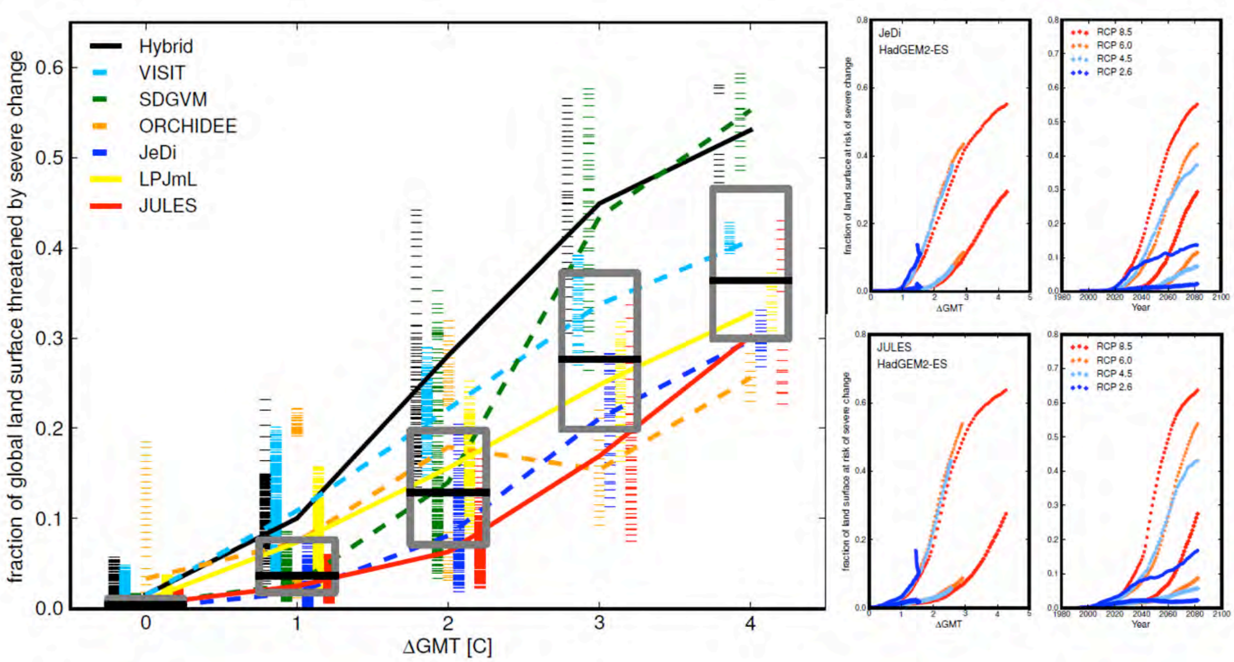


Figure 4-2: Fraction of land surface at risk of severe ecosystem change as a function of global mean temperature change for all ecosystems models, global climate models and RCPs

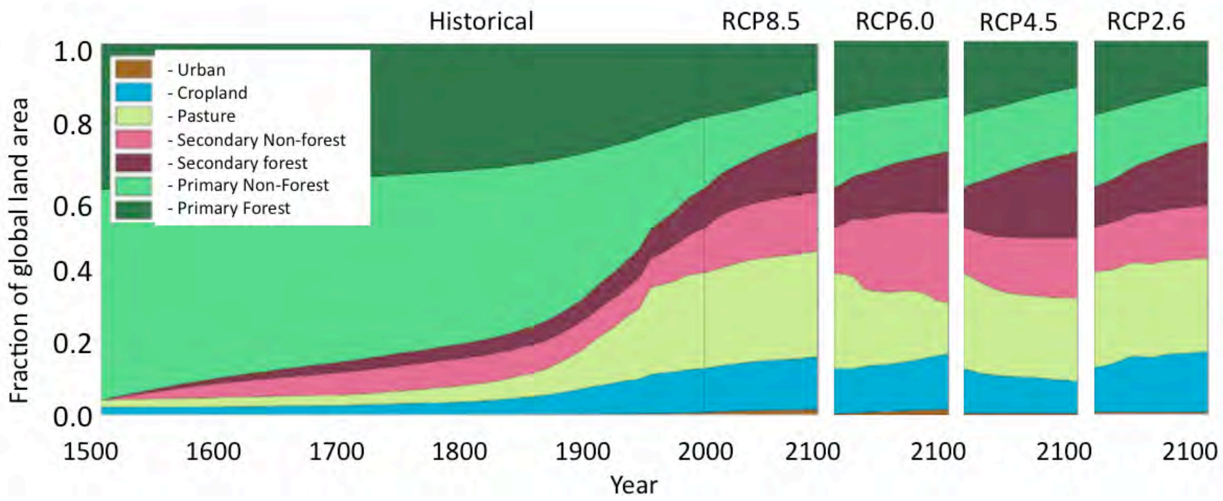


Figure 4-3: Proportion of global land cover occupied by primary and secondary vegetation (forest and non-forest), cropland, pasture and urban land, from satellite data and historical reconstructions up to 2005, and from scenarios associated with the RCPs from 2005 to 2100.

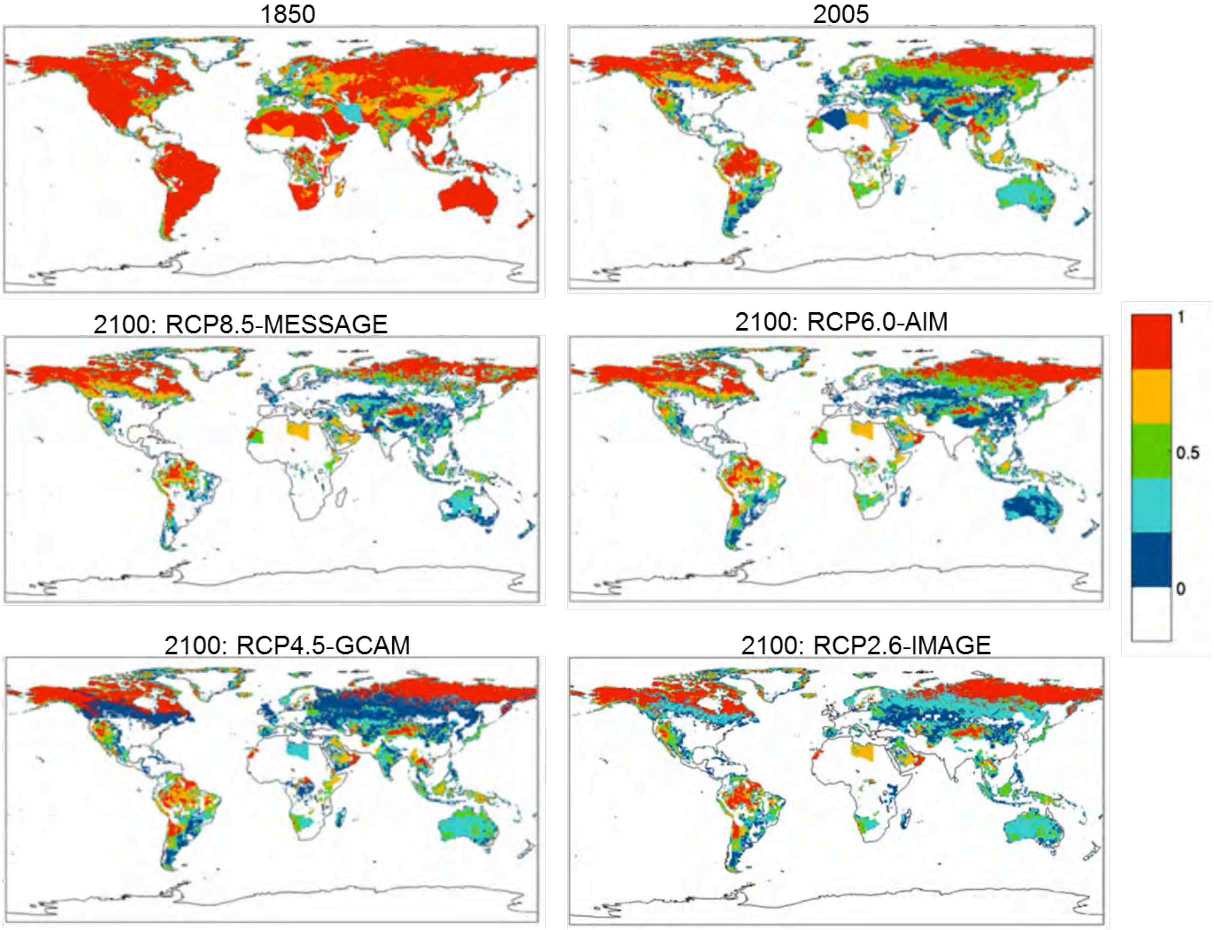


Figure 4-4: Fractional cover of primary vegetation at 1850 and 2005 based on satellite data and historical reconstructions, and at 2100 in scenarios associated with the RCPs.

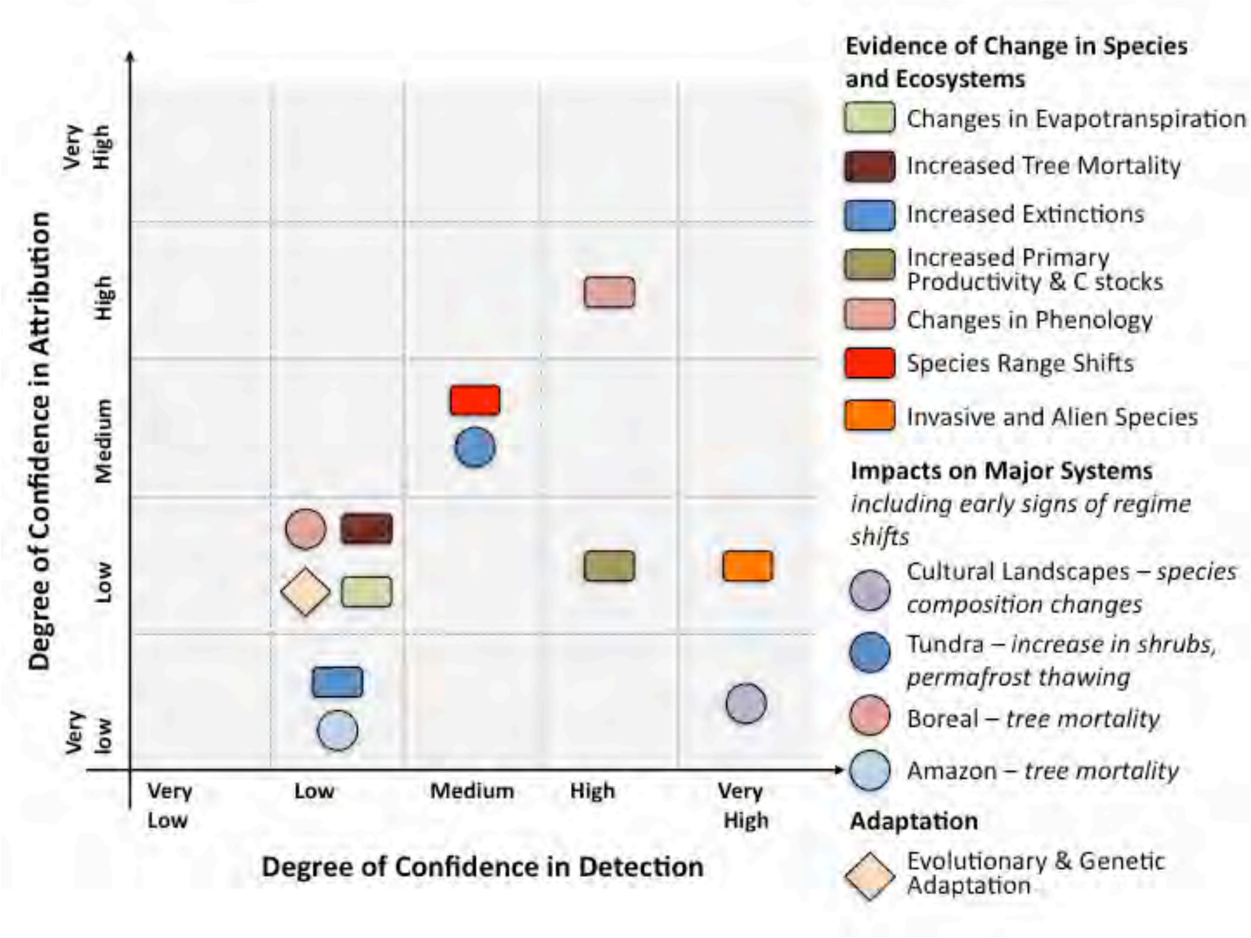


Figure 4-5: Confidence in Detection and Attribution of observed responses of terrestrial ecosystems to climate change.

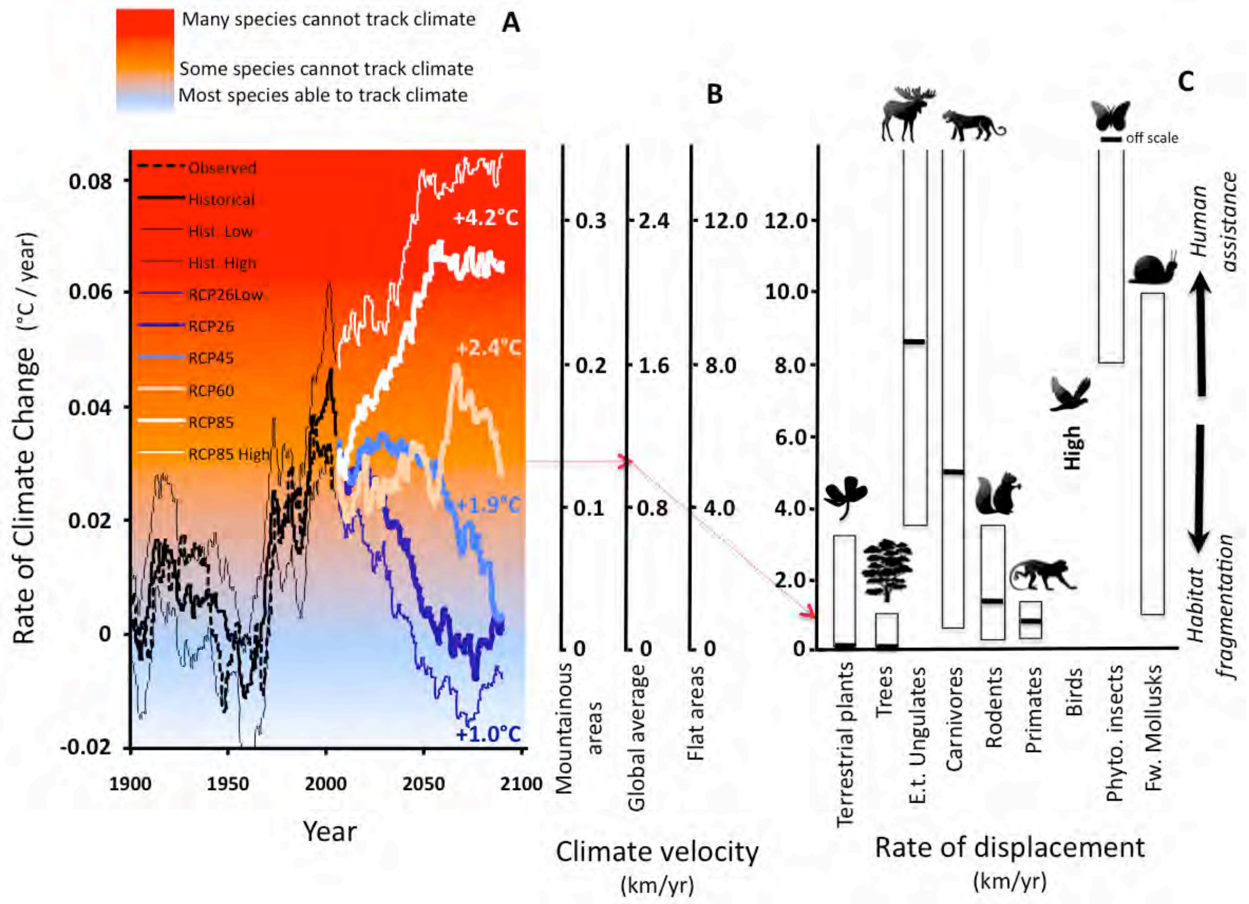
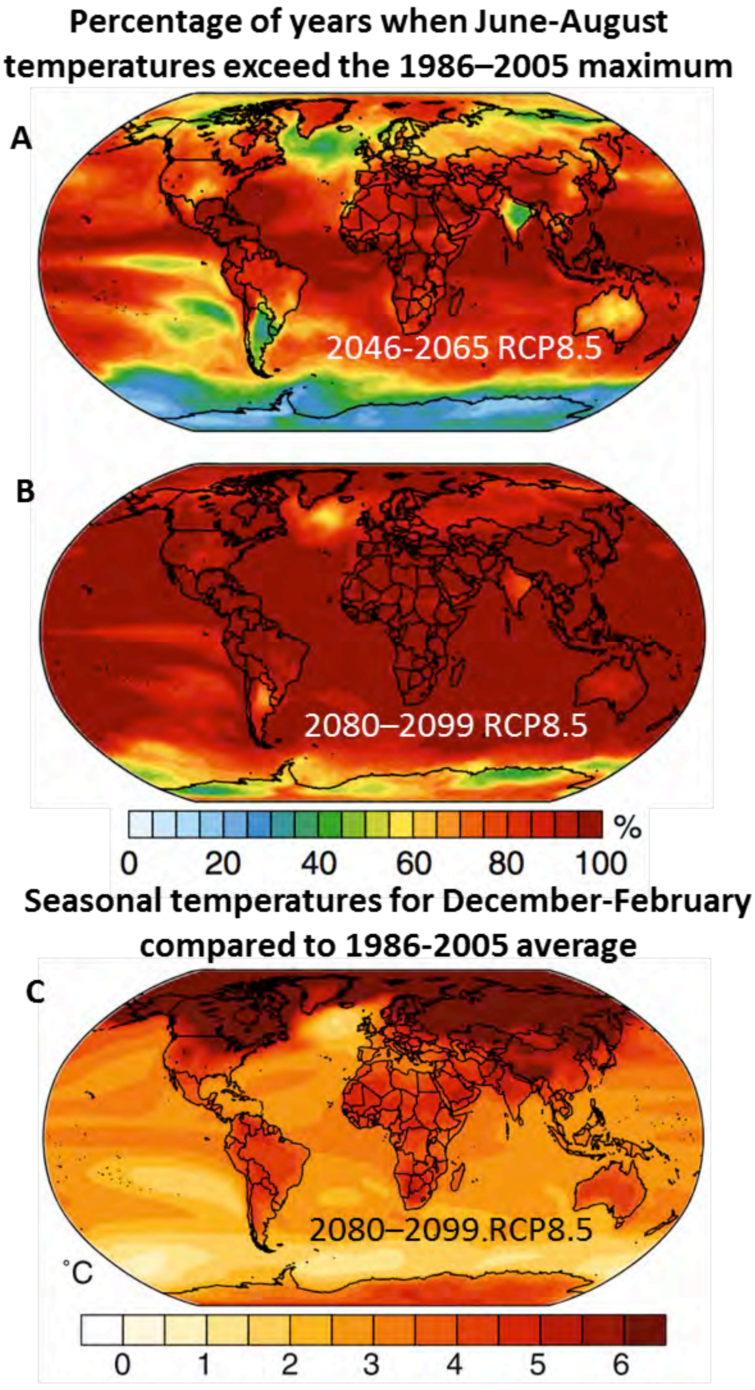


Figure 4-6: Rate of climate change, climate velocity and rate of displacement



From: Diffenbaugh & Giorgi. 2012. Climatic Change 114-813-822

Figure 4-7: Vulnerability of terrestrial biomes to future climate change.

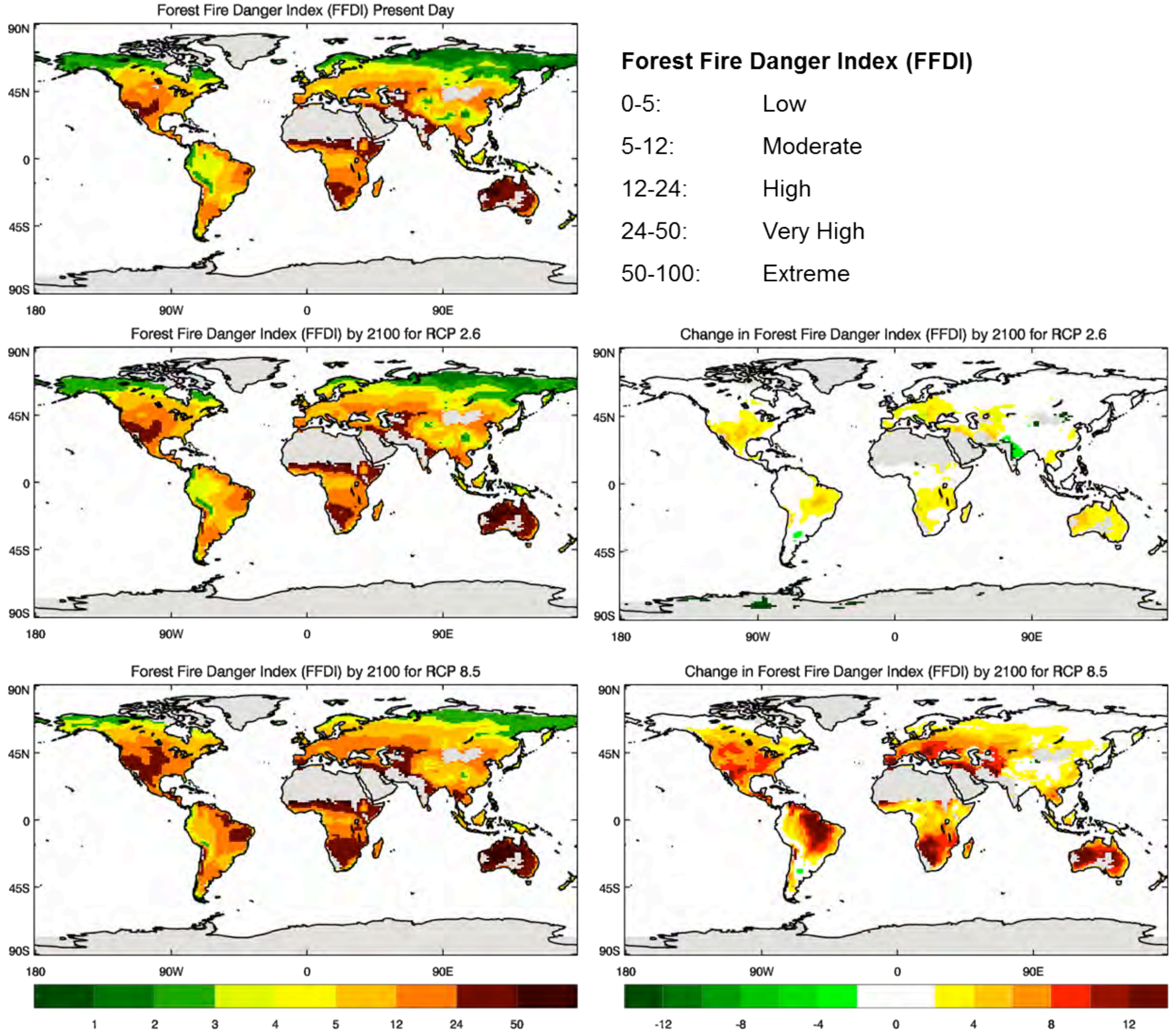


Figure 4-8: Forest Fire Danger Index simulated with the HadGEM2-ES Earth System Model.

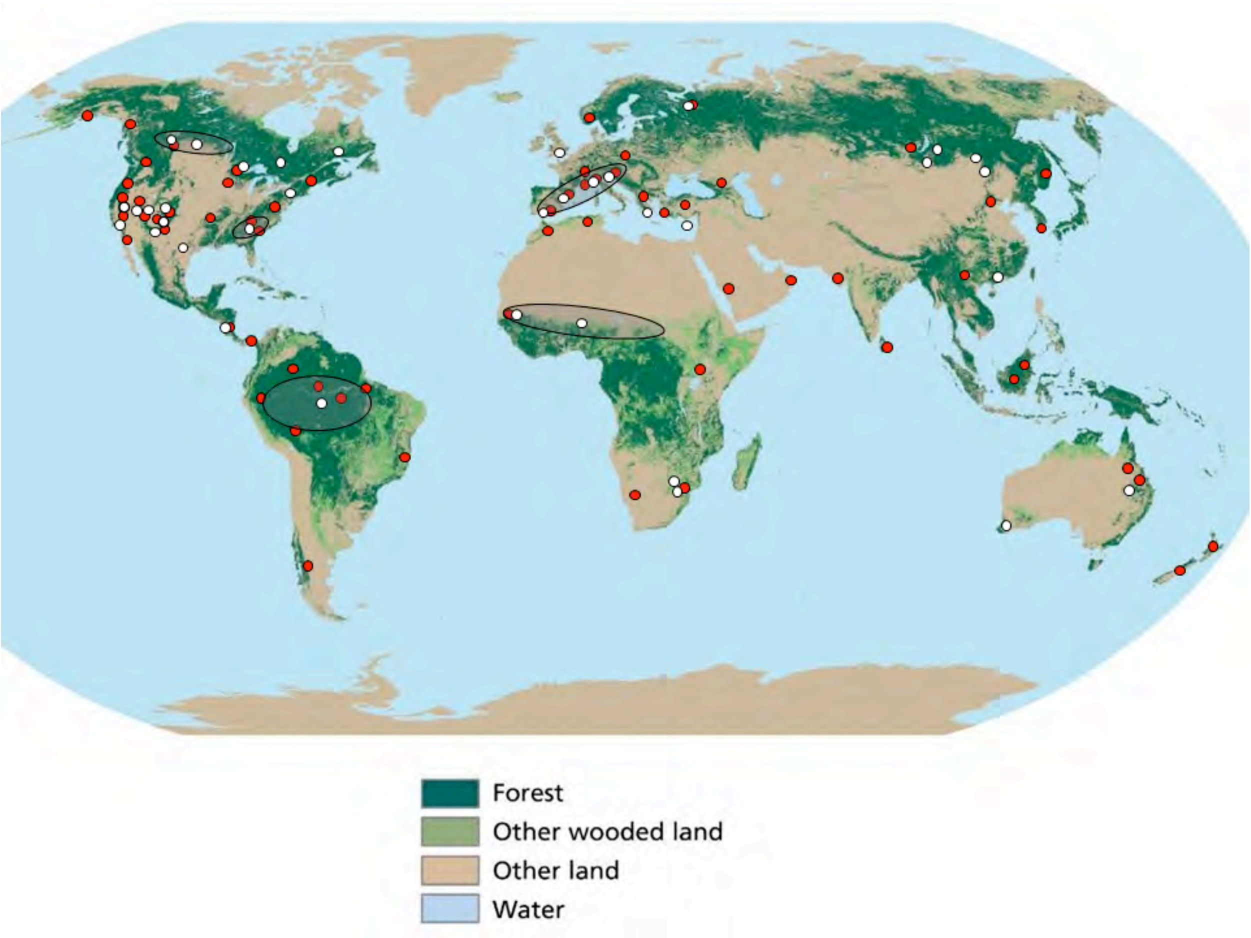


Figure 4-9: Forest mortality related to climatic stress.

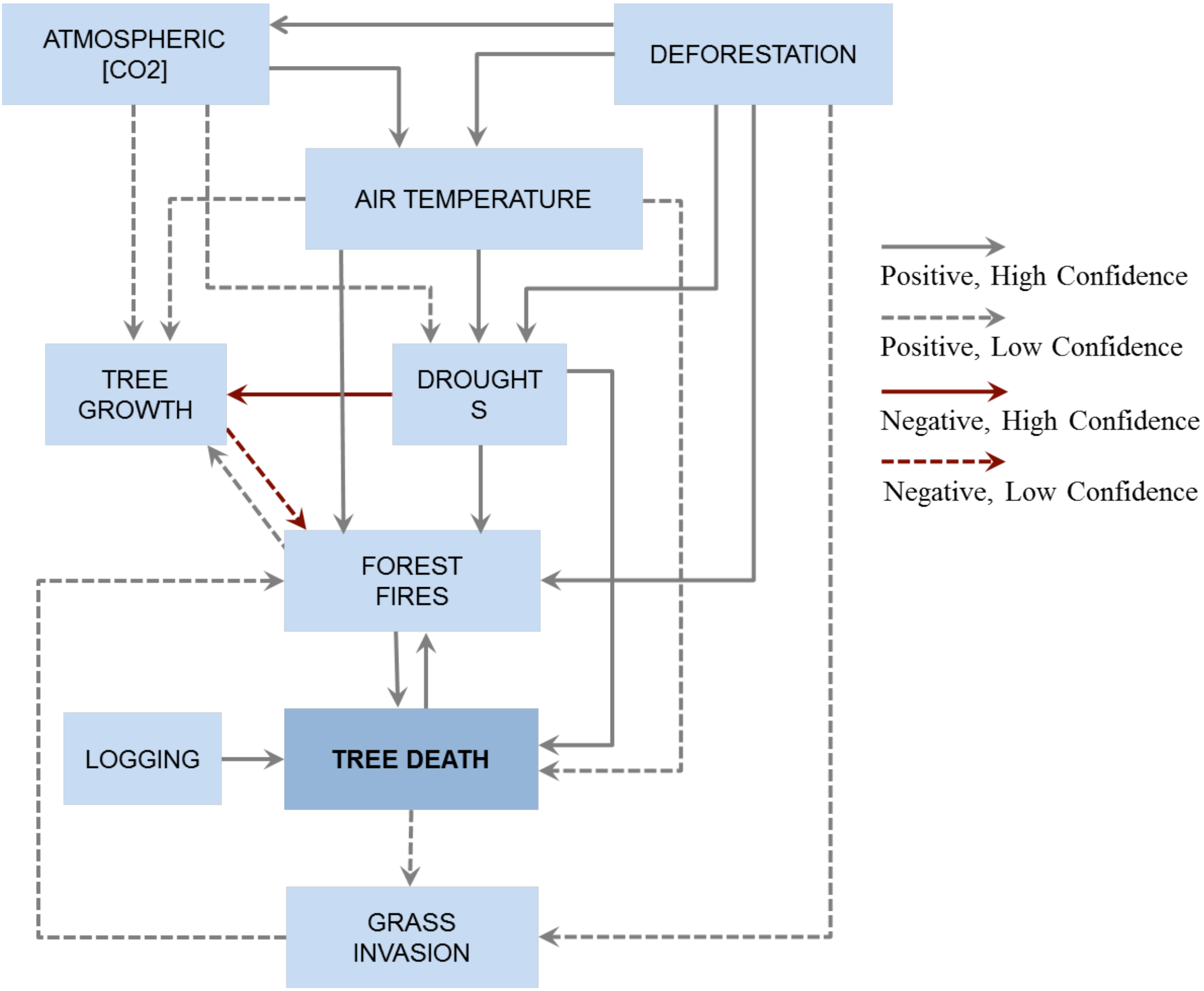


Figure 4-10: Amazon Die back.

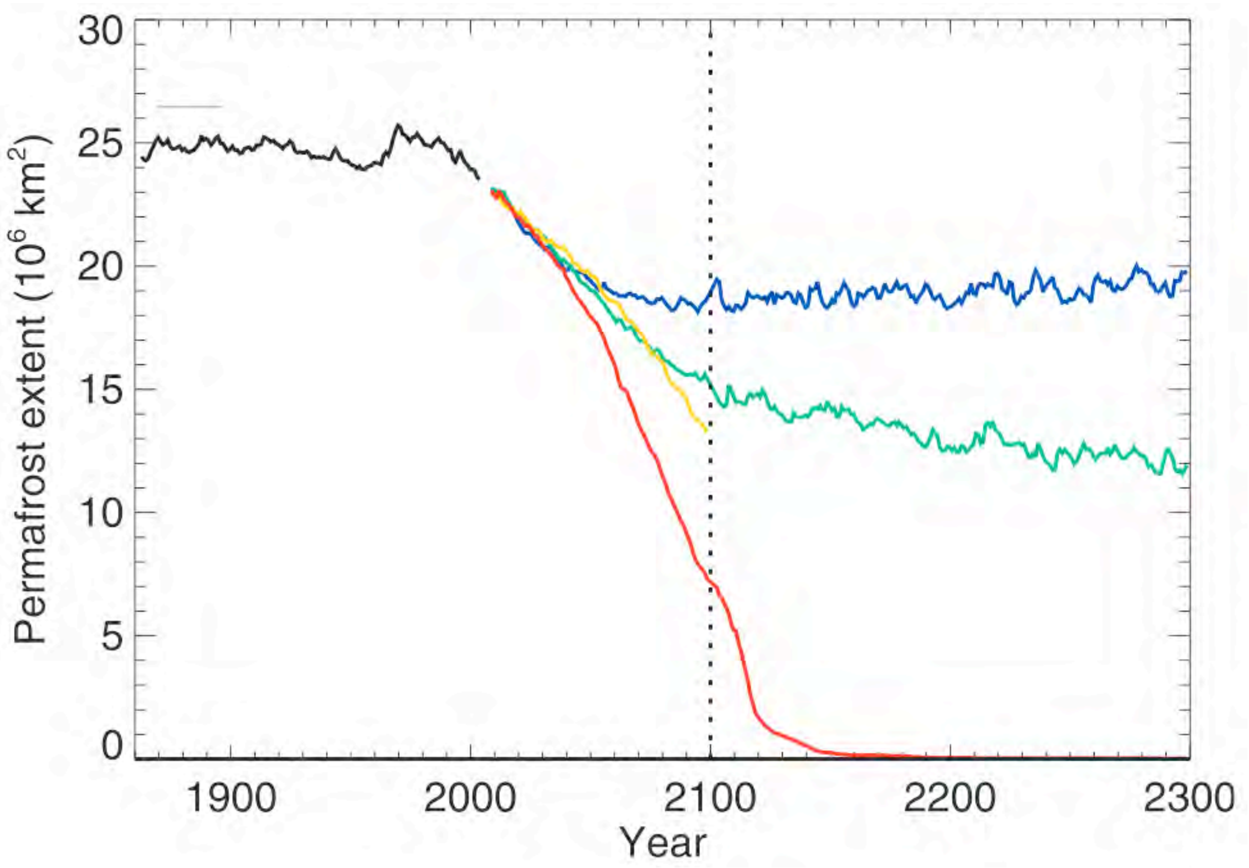


Figure 4-11: Simulations of past and future northern hemisphere permafrost area with a maximum thaw depth less than 3m deep.

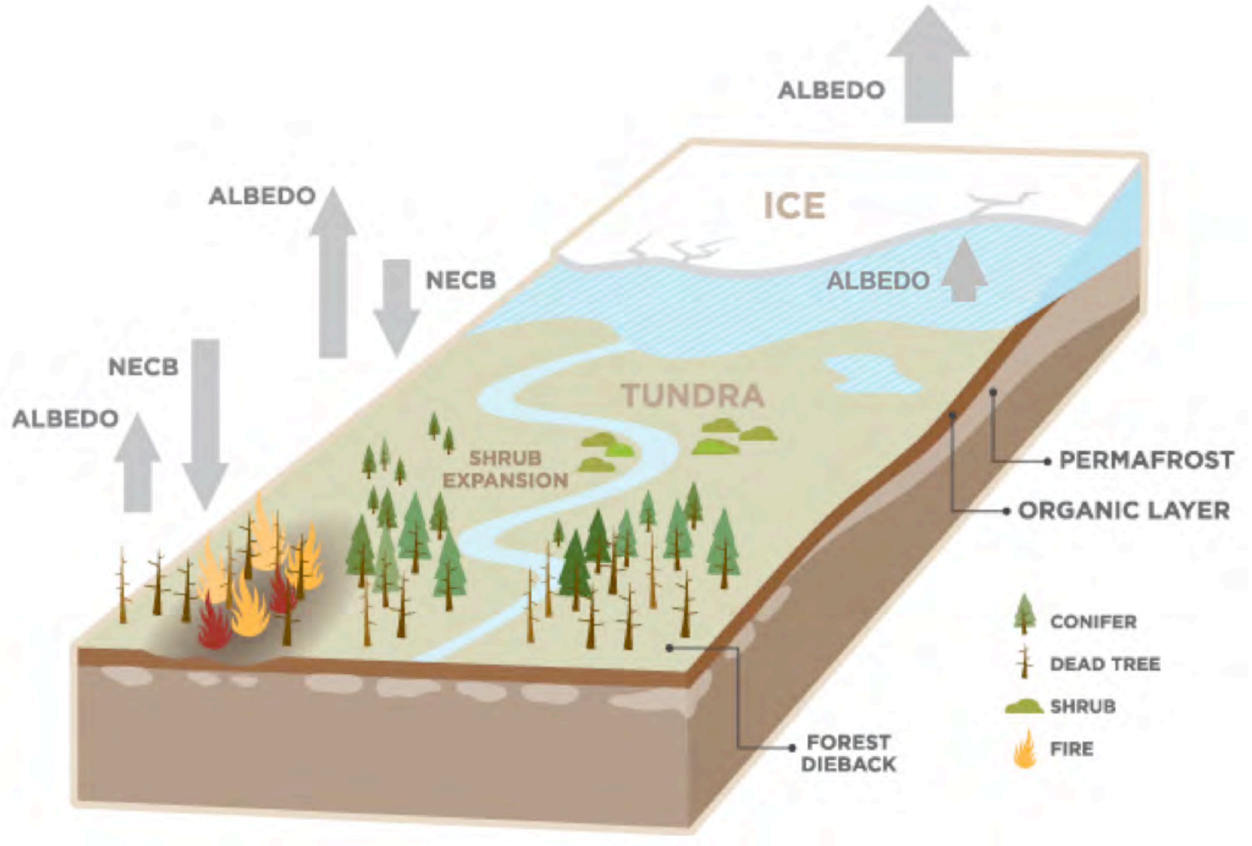


Figure 4-12: Tundra biome shift.

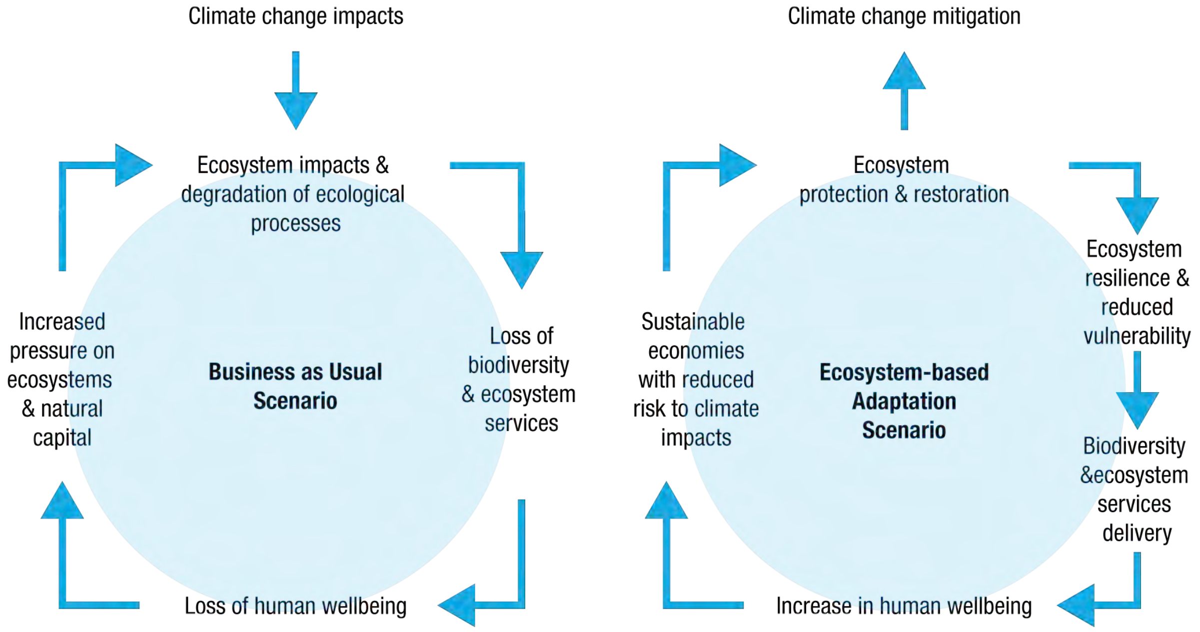


Figure EA-1: Adapted from Munang *et al.* (2013). Ecosystem based adaptation approaches to adaptation can utilize the capacity of nature to buffer human systems from the adverse impacts of climate change through sustainable delivery of ecosystems services. A) Business as Usual Scenario in which climate impacts degrade ecosystems, ecosystem service delivery and human well-being B) Ecosystem-based Adaptation Scenario which utilizes natural capital and ecosystem services to reduce climate-related risks to human communities.

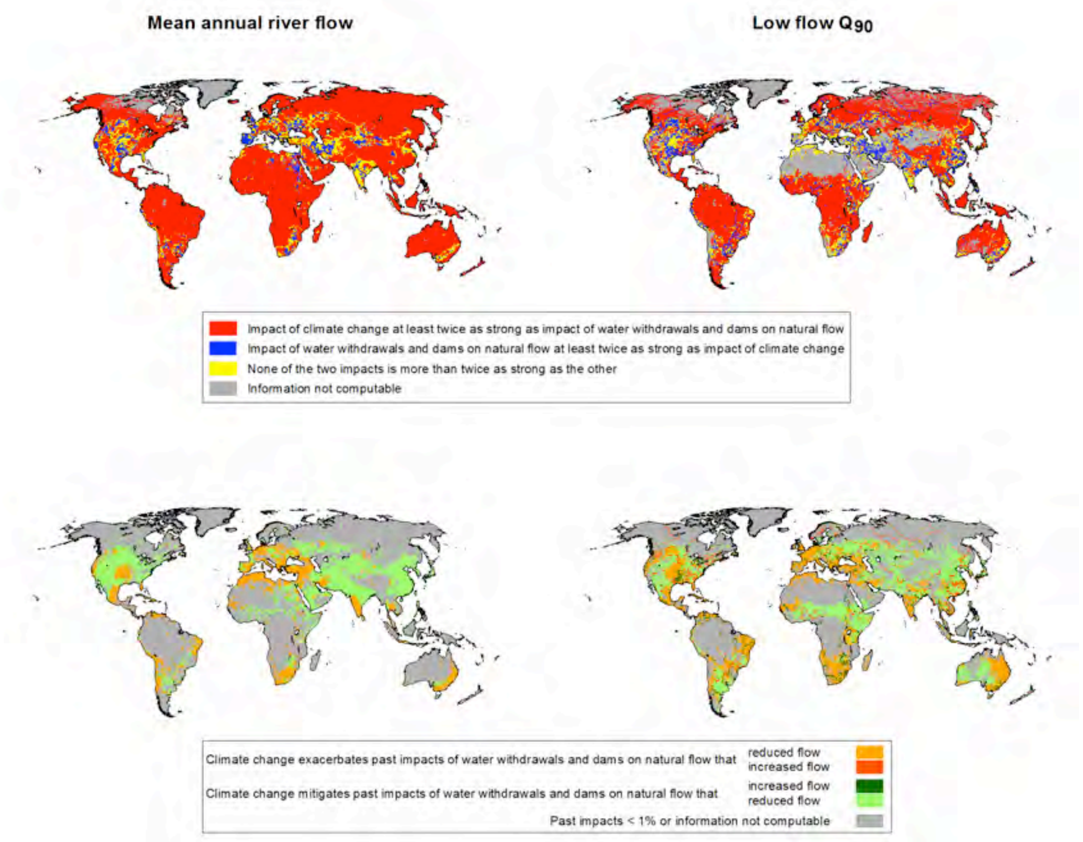


Figure RF-1: Impact of climate change on the ecologically relevant river flow characteristics mean annual river flow and monthly low flow Q_{90} as compared to the impact of water withdrawals and dams on natural flows, as computed by a global water model (Döll and Zhang, 2010). Impact of climate change is the percent change of flow between 1961-1990 and 2041-2070 according to the emissions scenario A2 as implemented by the global climate model HadCM3. Impact of water withdrawals and reservoirs is computed by running the model with and without water withdrawals and dams that existed in 2002.

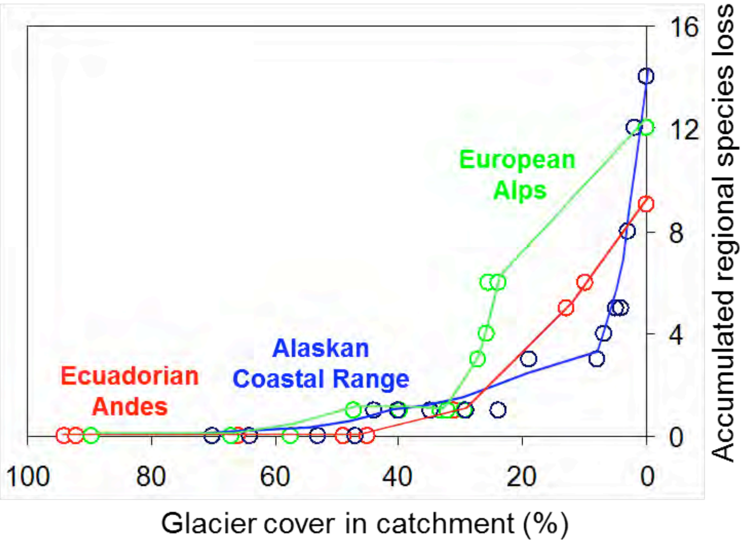
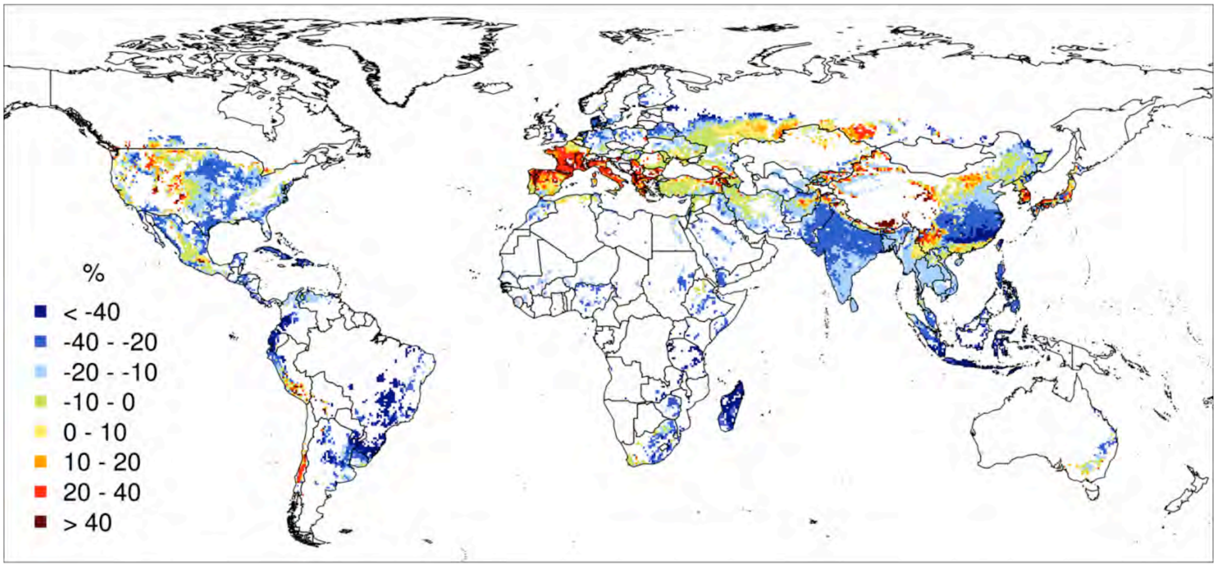


Figure RF-2: Accumulated loss of regional species richness (gamma diversity) as a function of glacial cover GCC. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%. Each data point represents a river site and lines are Lowess fits. Adapted by permission from Macmillan Publishers Ltd: *Nature Climate Change*, Jacobsen *et al.*, 2012, © 2012.

With CO_2 Effect



Without CO_2 Effect

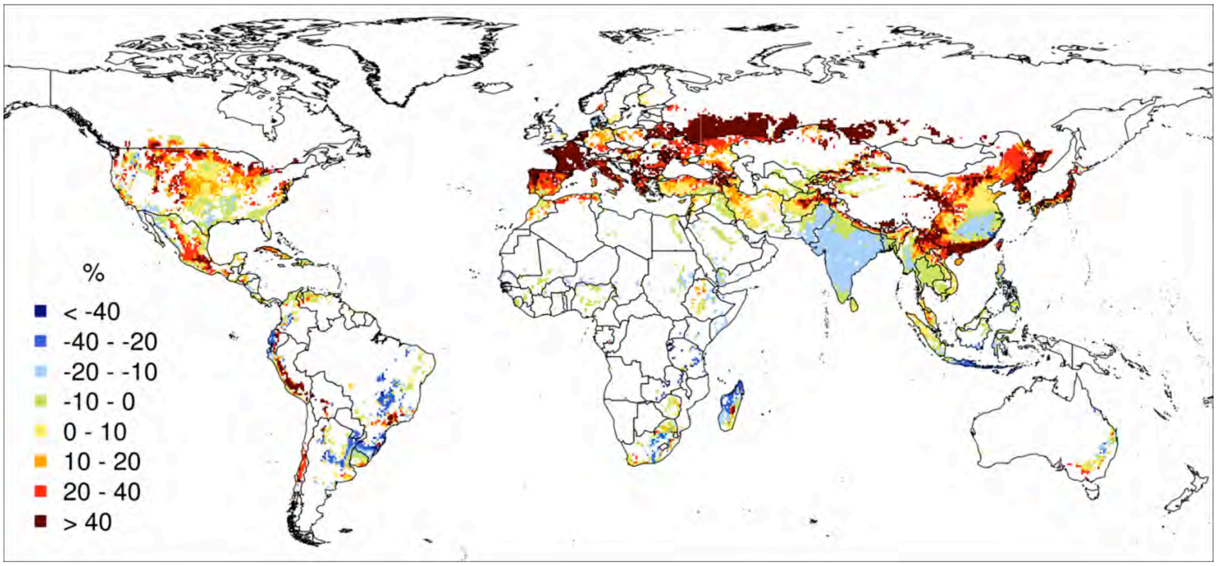


Figure VW-1: Percentage change (ensemble median across 19 GCMs used to force a vegetation and hydrology model) in net irrigation requirements of 12 major crops by the 2080s, assuming current extent of irrigation areas and current management practices. Top: impacts of climate change only; bottom: additionally considering physiological and structural crop responses to increased atmospheric CO_2 concentration. Taken from Konzmann *et al.* (2013).

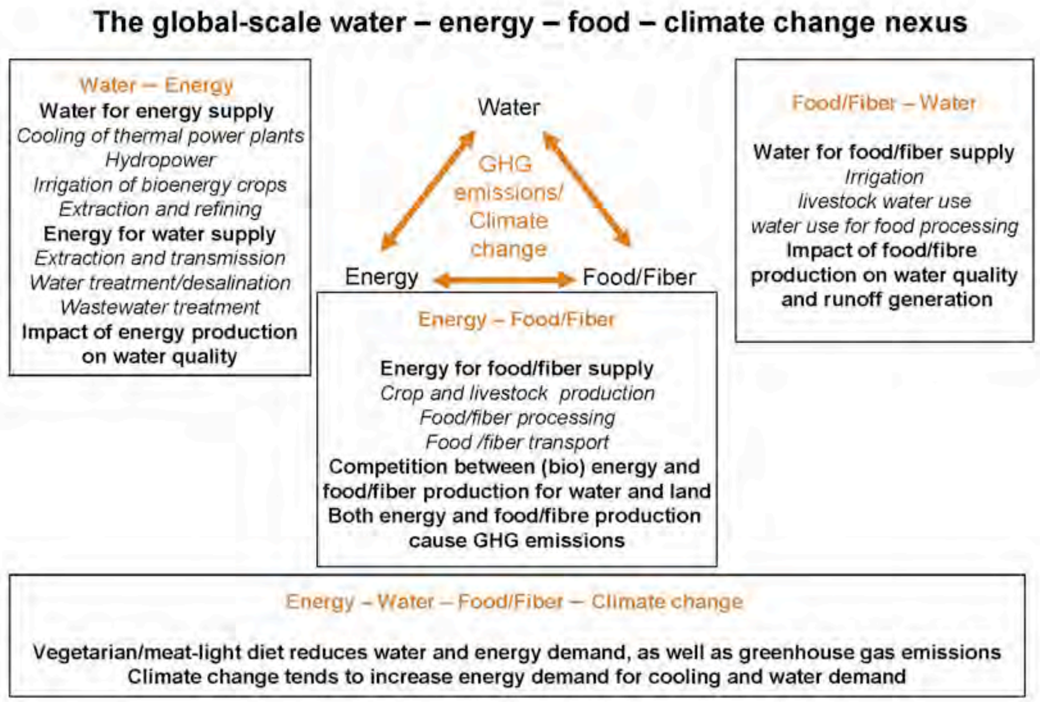


Figure WE-1: The water-energy-food nexus as related to climate change.