

## Chapter 4. Terrestrial and Inland Water Systems

### Coordinating Lead Authors

Robert Scholes (South Africa), Josef Settele (Germany)

### Lead Authors

Richard Betts (UK), Stuart Bunn (Australia), Paul Leadley (France), Daniel Nepstad (USA), Jonathan Overpeck (USA), Miguel Angel Taboada (Argentina)

### Contributing Authors

Craig Allen (USA), Bill Anderegg (USA), Celine Bellard (France), Paulo Brando (Brazil), Franck Courchamp (France), Wendy Foden (South Africa), Dieter Gerten (Germany), Scott Goetz (USA), Nicola Golding (UK), Patrick Gonzales (USA), Ed Hawkins (UK), Thomas Hickler (Germany), Josh Lawler (USA), Heike Lischke (Switzerland), Georgina Mace (UK), Melodie McGeoch (Australia), Camille Parmesan (USA), Richard Pearson (USA), Beatriz Rodriguez-Labajos (Spain), Rebecca Shaw (USA), Stephen Sitch (UK), Klement Tockner (Germany), Marten Winter (Germany)

### Review Editors

Andreas Fischlin (Switzerland), Jose Moreno (Spain), Terry Root (USA)

### Volunteer Chapter Scientist

Marten Winter (Germany)

### Contents

Executive Summary

4.1. Past Assessments

4.2. A Dynamic and Inclusive View of Ecosystems

4.2.1. Ecosystems as Adaptive Entities

4.2.2. What the Paleoecological Record Can and Cannot Tell Us

4.2.3. Landscapes and Social-Ecological Systems

4.2.4. Multiple Stressors and the Role of Climate Change

4.2.4.1. Land-Use and Cover Change (LUCC)

4.2.4.2. Nitrogen Deposition

4.2.4.3. Tropospheric Ozone

4.2.4.4. Rising CO<sub>2</sub>

4.2.4.5. Diffuse Versus Direct Radiation

4.2.4.6. Invasive and Alien Species

4.3. Vulnerability of Terrestrial and Freshwater Ecosystems to Climate Changes

4.3.1. The Importance of Changes in Disturbance Regime

4.3.2. Evidence of Change in Ecosystems

4.3.2.1. Phenology

4.3.2.2. Primary Productivity

4.3.2.3. Biomass and Carbon Stocks

4.3.2.4. Evapotranspiration and its Role in the Terrestrial Water Cycle

4.3.2.5. Changes in Species Range, Abundance, and Extinction

4.3.3. Impacts on Major Systems

4.3.3.1. Forests and Woodlands

4.3.3.2. Rangelands and Drylands, including Mediterranean-type Systems

4.3.3.3. Rivers, Lakes, Wetlands, and Peatlands

- 1 4.3.3.4. Tundra, Alpine, Permafrost Systems  
2 4.3.3.5. Highly Human-Modified Systems - Plantations, Bioenergy Systems, Urban Ecosystems,  
3 Cultural Landscapes  
4 4.3.4. Impacts on Key Services  
5 4.3.4.1. Habitat for Biodiversity  
6 4.3.4.2. Pollination, Pest and Disease Regulation  
7 4.3.4.3. Climate Regulation Services  
8 4.3.4.4. Potable Water Supply  
9  
10 4.4. Adaptation and its Limits  
11 4.4.1. Autonomous Adaptation by Ecosystems and Wild Organisms  
12 4.4.1.1. Phenological and Physiological  
13 4.4.1.2. Evolutionary and Genetic  
14 4.4.1.3. Migration of Species  
15 4.4.2. Human-Assisted Adaptation  
16 4.4.2.1. Reduction of Non-Climate Stresses and Restoration of Degraded Ecosystems  
17 4.4.2.2. The Size, Location, and Layout of Protected Areas  
18 4.4.2.3. Landscape and Watershed Management  
19 4.4.2.4. Assisted Migration  
20 4.4.2.5. Ex Situ Conservation  
21 4.4.3. Consequences and Costs of Inaction and Benefits of Action  
22 4.4.4. Unintended Consequences of Adaptation and Mitigation Actions in This and Other Sectors  
23  
24 4.5. Emerging Issues and Key Uncertainties  
25

#### 26 Frequently Asked Questions

- 27 4.1: How does climate change contribute to species extinction?  
28 4.2: Why does it matter that ecosystems are altered by climate change?  
29 4.3: What are the non-greenhouse gas effects of rising carbon dioxide?  
30 4.4: What costs are caused by changes in ecosystem services due to climate change?  
31 4.5: What are the opportunities for better managing ecosystems under climate change?  
32 4.6: Can land-use and land-cover changes cause changes in climate?  
33 4.7: Will the number of alien species increase due to climate change?  
34

#### 35 Cross-Chapter Boxes

- 36 CC-EA. Ecosystem Based Approaches to Adaptation - Emerging Opportunities  
37 CC-RF. Impact of Climate-Change on Freshwater Ecosystems due to Altered River Flow Regimes  
38 CC-VW. Active Role of Vegetation in Altering Water Flows Under Climate Change  
39 CC-WE. The Water-Energy-Food Nexus as Linked to Climate Change  
40

#### 41 References

42  
43

#### 44 Executive Summary

45

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

1  
2 **Few ecosystems can now be considered to be unaffected by human activity.** Vegetation cover classed as  
3 “primary” and essentially undisturbed by humans is estimated with *high confidence* to have decreased from  
4 approximately 95% of the global land area in 1500 AD to less than 40% at the start of the 21<sup>st</sup> Century, with half of  
5 this reduction being at the expense of primary forest. [4.2.1, 4.2.3, 4.2.4] **There is *medium confidence* that**  
6 **significant feedbacks exist between terrestrial ecosystems and the climate. Thus local, regional and global**  
7 **climate may be affected as ecosystems are altered, through climate change itself or other mechanisms, such as**  
8 **conversion to agriculture or human settlement.** These climate feedbacks are driven by changes in surface albedo,  
9 evapotranspiration and greenhouse gas emissions. The regions where the climate is affected may be different from  
10 the location of the ecosystem change. [e.g. 4.3.3.4]

11  
12 **There is *high confidence* for freshwater ecosystems and *medium confidence* for terrestrial ecosystems that**  
13 **direct human impacts such as land-use change, pollution and water resource development will continue to**  
14 **dominate the threats to ecosystems, with climate change becoming an increasing additional stress through the**  
15 **century, especially for high-warming scenarios such as RCP6.0 and RCP8.5.** [4.3.3] Model-based projections  
16 imply that direct land cover change will continue to dominate over climate-induced change for low to moderate  
17 warming scenarios at global scales (e.g., RCP2.6 to RCP6.0). However, in many areas not subject to intensive  
18 human disturbance, there is *high confidence* that even lower levels of projected future climate changes will result in  
19 changes in large-scale ecosystem character depending on the nature of regional climate changes. Such changes may  
20 not be fully apparent for several decades after reaching the critical regional climate state, due to long response times  
21 in ecological systems (*medium confidence*). For higher warming scenarios, some model projections imply climate-  
22 driven large-scale ecosystem changes which become comparable with direct human impacts at the global scale  
23 (*medium confidence*). There is *high confidence* that rising water temperatures will lead to shifts in freshwater species  
24 distributions and compound water quality problems, especially in those systems experiencing high anthropogenic  
25 loading of nutrients. There is *medium confidence* that changes in precipitation will significant alter ecologically  
26 important attributes of flow regimes in rivers and wetlands and exacerbate impacts from human water use in  
27 developed river basins. [Box CC-RF, 4.3.3.3]

28  
29 **There is *high confidence* that the capacity of many species to respond to climate change will continue to be**  
30 **constrained by non-climate factors,** including but not limited to the simultaneous presence of land-use changes,  
31 habitat fragmentation and loss, competition with alien species, exposure to novel pests and diseases, nitrogen  
32 loading, increasing carbon dioxide and tropospheric ozone. [Figure 4-1, 4.2.4-4.2.4.6, 4.3.3-4.3.3.5]

33  
34 **There is *high confidence* that a changing climate exacerbates other threats to biodiversity. In some systems,**  
35 **such as high altitude and latitude freshwater and terrestrial ecosystems, there is *high confidence* that climate**  
36 **changes exceeding those projected under RCP2.6 will lead to major changes in species distributions and**  
37 **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  
38 the nature of the projected regional climate change, the confidence in specific future ecosystem changes is limited  
39 by the confidence assigned to regional climate change projections by Working Group I.

40  
41 **There is *high confidence* that plants and animal species have moved their ranges, altered their abundance and**  
42 **shifted their seasonal activities in response to climate change in the past. There is also *high confidence* that**  
43 **they are doing so now in many regions and will continue to do so in response to projected future climate**  
44 **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  
45 and higher in altitude in response to a warming climate are well established for the distant (*very high confidence*)  
46 and recent past (*medium confidence*). *High confidence* in these past responses, coupled with projections from a  
47 diversity of models and studies provide *high confidence* that such responses will be the norm with continued  
48 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  
49 large changes in local abundance under all climate change scenarios: abundance declining in areas where climate  
50 becomes unfavorable and potentially increasing in areas where climate becomes more favorable. [4.3.2.5] There is  
51 *high confidence* that such changes in species abundance lead to changes in community composition and ecosystem  
52 function. There is *high confidence*, based on extensive ground and satellite-based measurements that the seasonal  
53 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  
54 models of the seasonal activities of species indicate that climate warming disrupts species life cycles and

1 interactions between species, as well as altering ecosystem function. [4.3.2.1, 4.4.1.1] At local scales, observed and  
2 modelled species responses sometimes differ from qualitative predictions based on global scale indices of warming;  
3 this can often be explained by large variation in local scale climate response to global warming, changes in climate  
4 factors other than average temperature, non-climatic determinants of species distributions, interactions between  
5 climate and other simultaneous global change factors such as nitrogen deposition, and species interactions. [4.3.2.1,  
6 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  
7 projected climatic changes, so species responses inferred from the past only give indications, especially at the local  
8 scale. [4.2.2]  
9

10 **There is *high confidence* that climate change is increasing the likelihood of the establishment, growth, spread**  
11 **and survival of some invasive alien species populations in some regions.** Alien invasive species are more likely  
12 than native species to have traits that favor their survival and reproduction under changing climates. Species  
13 movement into areas where they were not present historically will be driven both by climate change and by  
14 increased dispersal opportunities associated with human activities. [4.2.4.6]  
15

16 **There is *medium confidence* that even for mid-range rates of climate change (i.e., RCP4.5 and RCP6.0**  
17 **scenarios) many species will be unable to move fast enough to track suitable climates.** Over the last several  
18 decades many species have tracked changes in climate. However, there is *medium confidence* that some species have  
19 been unable to track recent climatic changes. [4.3.2.5] Populations of species that cannot track future climate change  
20 by migrating will find themselves in unfavorable climates and are unable to expand into newly climatically suitable  
21 areas. Species in large flat areas are particularly vulnerable because they must migrate over longer distances to keep  
22 up with climate change than species in mountainous regions. Species with low migration capacity will also be  
23 especially vulnerable: examples include most trees, many plants, and some small mammals. Combinations of low  
24 migration capacity and large flat areas are projected to pose the most serious problems for tracking climate; for  
25 example, there is *medium confidence* that even the maximum observed and modelled migration rates for mid- and  
26 late-successional tree species will be insufficient to track climate change in flat areas even at moderate rates of  
27 climate change. There is *high confidence* that barriers to migration such as mountain ranges, dams, habitat  
28 fragmentation and occupation of habitat by competing species substantially reduce the ability of species to migrate  
29 to more suitable climates. There is *high confidence* that outlier populations (e.g., collections in botanical gardens or  
30 parks), as well as intentional and accidental anthropogenic transport will speed migration. [4.3.2.5, 4.3.3.3]  
31

32 **There is *high confidence* that large magnitudes of climate change will negatively impact species with**  
33 **populations that are primarily restricted to protected areas, mountaintops or mountain streams, even those**  
34 **that potentially migrate fast enough to track suitable climates.** [4.3.2.5, 4.3.4.1] Climate change is projected with  
35 *high confidence* to either create unsuitable climates for species that remain in these areas, or force species out of  
36 protected areas and off mountaintops. These effects are foreseen to be modest for low magnitudes of climate change  
37 (e.g., RCP 2.6) and very high for the highest magnitudes of projected climate change (e.g., RCP 8.5). There is *high*  
38 *confidence* that species have already started to migrate out of protected areas and towards mountaintops over the last  
39 several decades due to a warming climate. [4.3.2.5, 4.3.4.1]  
40

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

1 the specific case of Central American amphibians, there is *medium confidence* that recent warming has played a role  
2 in their extinctions. [4.3.2, 4.3.2.5]

3  
4 **It is *virtually certain* that the carbon stored in land and freshwater ecosystems in the form of plant biomass  
5 and soil organic matter has increased over the past two decades in what is known as the terrestrial carbon  
6 sink. There is *low confidence* that the transfer of carbon dioxide from the atmosphere to the land will  
7 continue at a similar rate for the remainder of the century. There is *high confidence* that the terrestrial  
8 carbon sink is offset to a large degree by carbon released to the atmosphere through forest conversion to farm  
9 and grazing land and through forest degradation [4.2.4.1, 4.3.3.1]. There is *medium confidence* that the  
10 carbon stored thus far in terrestrial ecosystems is vulnerable to loss back to the atmosphere as a result of  
11 climate change (including indirect effects such as increased risk of fires and pest outbreaks) and land-use  
12 change.** Terrestrial and freshwater ecosystems have been responsible for the uptake of about a quarter of all  
13 anthropogenic CO<sub>2</sub> emissions in the past half century. [4.3.2.2 and 4.3.2.3] The net fluxes out of the atmosphere and  
14 into plant biomass and soils show large year-to-year variability. As a result there is *low confidence* in the ability to  
15 determine whether the net fluxes into or out of terrestrial ecosystems at the global scale have increased or decreased  
16 over the past two decades. There is *high confidence* that the factors causing the current increase in land carbon  
17 include the positive effects of rising CO<sub>2</sub> on plant productivity, a warming climate, and recovery from past  
18 disturbances, but *low confidence* regarding the relative contribution by each of these and other factors. [4.2.4.1,  
19 4.2.4.2, 4.2.4.4, 4.3.2.2] Experiments and modelling studies provide *medium confidence* that increases in CO<sub>2</sub> up to  
20 about 600 ppm will continue to enhance photosynthesis and plant water-use efficiency, but at a diminishing rate.  
21 [4.2.4.4]. There is also *medium confidence* that other factors associated with global change, including high  
22 temperatures, rising ozone concentrations and in some places drought, decrease plant productivity by comparable  
23 amounts [4.2.4.3, Box 4-3]. Models provide *high confidence* that nitrogen availability will limit the response of  
24 many natural ecosystems to rising CO<sub>2</sub> [4.2.4.2]. There are few field-scale experiments on ecosystems at the highest  
25 CO<sub>2</sub> concentrations projected by RCP8.5 for late in the century, and none of these include the effects of other  
26 potential confounding factors [4.3.2.2, 4.2.2.3].

27  
28 **There is *medium confidence* that increases in the frequency or intensity of ecosystem disturbances due to fires,  
29 pest outbreaks, wind-storms and droughts have been detected in many parts of the world. There is *high*  
30 *confidence* that such changes, which are by definition beyond the range of historical natural variability, will  
31 alter the structure, composition and functioning of ecosystems.** There is *medium confidence* that such changes  
32 will often be manifested as relatively abrupt and spatially-patchy transitions following disturbances, rather than  
33 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]

34  
35 **There is evidence of an increase in tree mortality in many regions over the last decade, but there is *low*  
36 *confidence* in the detection of a global trend in increased mortality or in the attribution of such a global trend  
37 to climate change. In some regions, increased tree mortality is sufficiently intense and widespread as to result  
38 in forest dieback. Forest dieback constitutes a major risk because of its large impacts on biodiversity, wood  
39 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-  
40 2, Box 4-3].** In detailed regional studies, particularly in western and boreal North America, there is *high confidence*  
41 that observed tree mortality is detectable and can be attributed to the direct effects of high temperatures and drought,  
42 or to changes in the distribution and abundance of insect pests and pathogens related, in part, to warming.

43  
44 **Recent experimental, observational and modelling studies provide *medium confidence* that forests may be  
45 more sensitive to future climate change than reported in IPCC AR4 assessment and that tree mortality and  
46 forest dieback could become a problem in many regions much sooner than previously anticipated.** [4.3.3.1]  
47 There is *high confidence* that future climate change impacts on tree mortality and tree ranges could be large, but  
48 experimental, observational and modelling studies also indicate that there is *low confidence* associated with model-  
49 based projections of the details of these impacts. As such, projections of increased tree growth and enhanced forest  
50 C sequestration mediated by increasing growing season length, rising CO<sub>2</sub> concentrations and atmospheric N  
51 deposition are being viewed with increasingly greater caution due to the counter-balancing effects of mortality and  
52 dieback. [4.3.3.1] The consequences for the provision of timber and other wood products are projected to be highly  
53 variable between regions and products depending on the balance of the positive vs. negative effects of global  
54 change. [4.3.3.1, 4.3.3.5, 4.3.4]

1  
2 **In the Amazon, there is *medium confidence* that climate change alone will not lead to widespread forest loss**  
3 **during this century. However, there is also *medium confidence* that a combination of severe drought, land use**  
4 **and fire act together to transform mature forests to less dense, fire prone woodland and shrublands.**

5 Modelling studies project a range of changes in the regional climate of the Amazon, and very few indicate a state  
6 that cannot support rainforest. Nevertheless, many models still project a general drying tendency, and coupled with  
7 warming this may increase fire risk. Human land use is associated with fire, so a combination of direct human  
8 influence and climate change may still affect the Amazon. [4.3.3.1.3, Box 4-3]  
9

10 **There is *high confidence* that terrestrial and freshwater ecosystems can, when pushed by climate change,**  
11 **cross “tipping points” and abruptly change in composition, structure and function. There is *medium***  
12 ***confidence* that the crossing of these tipping points will result in significant increases in carbon emissions to**  
13 **the atmosphere.** This has happened many times in Earth history. [4.2.2]. There are plausible mechanisms,  
14 supported by experimental evidence and model results, for the existence of ecosystem tipping points in both boreal-  
15 arctic systems and the rainforests of the Amazon basin [Boxes 4-3 and 4-4], others may exist. There is a plausible  
16 but *low confidence* case that continued climate change could push the boreal-arctic system across such a tipping  
17 point in this century and cause an abrupt transformation of the ecology and albedo of this region, as well as the  
18 release of greenhouse gases from the thawing permafrost and burning forests. There is *high confidence* that adaption  
19 measures will be unable to prevent substantial change in the boreal-arctic system. There is also a plausible but *low*  
20 *confidence* case that continued climate change together with land-use change and fire activity could cause much of  
21 the Amazon forest to transform abruptly to more open, dry-adapted ecosystems, and in doing so, put a large stock of  
22 biodiversity at elevated risk, and create a large new net greenhouse gas source to the atmosphere. [4.3.3.1]. There is  
23 *medium confidence* that the combination of climate change and land-use change in the Amazon will cause  
24 accelerated drying and drought frequency in the region and *low confidence* that these Amazon changes will affect  
25 rainfall in agricultural regions elsewhere on the planet. [4.3.3.1]. There is *medium confidence* that rigorously applied  
26 adaptation measures could lower the risk of abrupt change in the Amazon, as well as the impacts of that change.  
27 [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  
28 caused a steep decline in deforestation in the Amazon since 2005 that have decreased anthropogenic carbon  
29 emissions to the atmosphere by 1.5%. [4.2.4.1, 4.3.3.1]  
30

31 **There is *high confidence* that management actions can reduce, but not eliminate, exposure to climate-driven**  
32 **ecosystem impacts, as well as increase ecosystem adaptability.** [4.4] The capacity for natural adaptation by  
33 ecosystems and their constituent organisms is substantial, but for many ecosystems and species there is *medium*  
34 *confidence* that this is insufficient to cope without substantial loss of species and ecosystem services, given the rate  
35 and magnitude of climate change projected under medium-range warming (e.g., RCP6.0) or high-range warming  
36 scenarios (e.g., RCP8.5). The capacity for ecosystems to adapt to climate change can be increased by reducing the  
37 other stresses operating on them; reducing the rate and magnitude of change; reducing habitat fragmentation and  
38 increasing connectivity; maintaining a large pool of genetic diversity and functional evolutionary processes; assisted  
39 translocation of slow moving organisms or those whose migration is impeded, along with the species on which they  
40 depend; and manipulation of disturbance regimes to keep them within the ranges necessary for species persistence  
41 and sustained ecosystem functioning. [4.4.1-4.4.1.2, 4.4.3]  
42

43 **There is *medium confidence* that management adaptation responses to climate change in some sectors will**  
44 **lead to unintended and unwanted outcomes for terrestrial and freshwater ecosystems.** For example, adaptation  
45 responses to counter increased variability of water supply for urban and agricultural use, such as building more and  
46 larger impoundments and increased water abstraction, will compound the direct effects of climate change in  
47 freshwater ecosystems. [4.3.3.3, 4.3.4.5] **There is *very high confidence* that the use of the terrestrial biosphere in**  
48 **climate mitigation actions, such as through introduction of fast-growing tree species for carbon sequestration**  
49 **or the conversion of forest to biofuel plantations, may lead to negative impacts on ecosystems and**  
50 **biodiversity.** The land use scenario accompanying the mitigation scenario RCP2.6, intended to avoid 2°C global  
51 warming, features large expansion of biofuel production, displacing natural forest cover. [4.2.4.1]  
52  
53  
54

#### 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

1 and parameters, and still persist' (Holling, 1973), and also in a broader sense of being able to adapt to change,  
2 without necessarily remaining within the same dynamical range (Walker *et al.*, 2004) and has been applied in the  
3 context of climate change (e.g. Morecroft *et al.*, 2012). One source of such adaptability is evolution within the  
4 populations of organisms making up the ecosystem. Natural selection operates on genetic variability against those  
5 individuals less able to survive, compete and successfully reproduce in the altered environment, leading to a shift,  
6 over generations, in the tolerance range of the population. Organisms also typically exhibit physiological,  
7 developmental or behavioral plasticity, within limits, that does not require genetic change. A particular case occurs  
8 when humans in the ecosystem use learning and technology to alter how they interact with the system. A third form  
9 of adaptation occurs when the configuration and functional form of interactions within an ecosystem change, in  
10 some cases leading to a new stable state ([www.regimeshifts.org](http://www.regimeshifts.org)). It occurs when the abundance of one or more  
11 species are greatly altered or are replaced by other species with similar functional attributes. In the extreme, this  
12 would constitute a change in ecosystem type.  
13

14 Field observations over the past century in numerous locations in boreal, temperate and tropical ecosystems have  
15 detected shifts of plant species at the biome level upwards in elevation and to higher latitudes (Gonzalez *et al.*,  
16 2010). These shifts have been formally or informally attributed to climate change ([INSERT TABLE 4-1 HERE  
17 Table 4-1, Figure 4-1). Projections of potential future vegetation indicate substantial susceptibility of ecosystems to  
18 biome shifts (Warszawski *et al.*, submitted; Figure 4-2, Box 4-3, Box 4-4).  
19

20 [INSERT TABLE 4-1 HERE

21 Table 4-1: Biome shifts from 1700 to the present from published field research that examined trends over periods >  
22 30 y for biomes in areas where climate (rather than land-use change or other factors) predominantly influenced  
23 vegetation, derived from a systematic analysis of published studies (Gonzalez *et al.* (2010). Pre-AR4 publications  
24 are included to provide a comprehensive review. Shift type: elevational (E), latitudinal (L), examined but not  
25 detected (N). Biomes (and abbreviations), from poles to equator: tundra and alpine (UA), boreal conifer forest (BC),  
26 temperate conifer forest (TC), temperate broadleaf forest (TB), temperate shrubland (TS), tropical grassland (RG),  
27 tropical woodland (RW). Rate of change in temperature (Temp.) and fractional rate of change in precipitation  
28 (Precip.) are derived from linear least squares regression of 1901-2002 data (Mitchell and Jones, 2005; Gonzalez *et al.*  
29 *et al.*, 2010). The table provides general regional climate trends at 50 km spatial resolution because the references do  
30 not give uniform site-specific climate data to compare across locations. The regional trends are consistent with local  
31 trends reported in each reference. \* rate significant at  $P \leq 0.05$ ].  
32

33 [INSERT FIGURE 4-1 HERE

34 Figure 4-1: Biome shifts from 1700 to the present at sites in Table 4-1, derived from Gonzalez *et al.* (2010).  
35 Temperature change is the rate from linear least squares regression of 1901-2002 temperatures (Mitchell and Jones,  
36 2005; Gonzalez *et al.*, 2010). Numbers refer to the sites in Table 4-1. Arrows indicate general direction of shifts.]  
37

38 [INSERT FIGURE 4-2 HERE

39 Figure 4-2: Fraction of land surface at risk of severe ecosystem change as a function of global mean temperature  
40 change for all ecosystems models, global climate models and RCPs. The colors represent the different ecosystems  
41 models, which are also horizontally separated for clarity. Results are collated in unit-degree bins, where the  
42 temperature for a given year is the average over a 30-year window centered on that year. The median in each bin is  
43 denoted by a black horizontal line. The grey boxes span the 25th and 75th percentiles across the entire ensemble.  
44 The short, horizontal stripes represent individual (annual) data points; the curves connect the mean value per  
45 ecosystem model in each bin. The solid (dashed) curves are for models with (without) dynamic vegetation  
46 composition changes. Right: Fraction of global land surface subject to severe ecosystem change as a function of  
47 global mean temperature (left panels) and time (right panels) for the JeDi (upper) and JULES (lower) dynamic  
48 global vegetation model driven by the HadGEM2-ES global climate model. The colors represent the different RCPs  
49 used to drive the climate model. Good agreement of results at different levels of global warming demonstrates that  
50 results are independent of the emissions scenario. (Reproduced from Warszawski *et al.*, submitted)]  
51  
52  
53



#### 4.2.2. *What the Paleocological 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; Arneeth *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; Danialu *et al.*, 2012). The paleoecological record thus provides *high confidence (robust evidence, high agreement)* that large climate change, such as that projected for the 21<sup>st</sup> 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 21<sup>st</sup> 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; Salzman *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 21<sup>st</sup> 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

1 will move, species mixtures will change, novel new plant communities will emerge, and significant carbon changes  
2 will take place, all in response to changing and often novel future climates (Williams and Jackson, 2007; Williams *et*  
3 *al.*, 2007b; MacDonald, 2010; Prentice *et al.*, 2011; Willis and MacDonald, 2011); see Section 4.3.2.5 for more  
4 specific information on migration rates). As such, the paleoecological record and models provide *high confidence*  
5 (*robust evidence, high agreement*) that it will be difficult or impossible to maintain many ecological systems in their  
6 current states if global warming exceeds 2 to 3°C, raising questions about the long-term viability of some current  
7 protected areas and conservation schemes, particularly where the objective is to maintain present-day species  
8 mixtures (Jackson and Hobbs, 2009; Hickler *et al.*, 2012).

9  
10 Much of the complex, time-dependent change at regional scales has not yet been simulated by models. The  
11 paleoecological record indicates that vegetation in many parts of the world has the potential to respond within years  
12 to a few decades to climate change (e.g., Watrin *et al.*, 2009; Williams *et al.*, 2009; Mueller *et al.*, 2009a; Harrison  
13 and Goni, 2010), and this same record thus provides a critical model evaluation opportunity that should be more  
14 thoroughly exploited to gain confidence in time-dependent simulations of future change, particularly given the  
15 complex role that interacting climate change and vegetation disturbance has played in the past (e.g., Marlon *et al.*,  
16 2009; Jackson *et al.*, 2009; Williams *et al.*, 2009; Daniu *et al.*, 2010; Dawson *et al.*, 2011).

17  
18 The paleoclimatic record also reveals that past radiative climate forcing change was slower than that anticipated for  
19 the 21st century (IPCC AR5 Chapter 12), but even these slower changes often drove surprisingly abrupt, or non-  
20 linear, regional change in terrestrial and aquatic systems (e.g., Harrison and Goni, 2010; Williams *et al.*, 2011), as  
21 did even slower orbitally-driven change during the most recent Holocene interglacial (e.g., Booth *et al.*, 2005;  
22 Kropelin *et al.*, 2008; Williams *et al.*, 2010b; Williams *et al.*, 2011). In all cases, specific periods of abrupt  
23 ecological response were regionally distinct in nature and were less synchronous for small, slow changes in forcing  
24 (e.g., during the Holocene) than for more global rapid changes listed at the start of this section. State-of-the-art  
25 climate and Earth system models are unable to simulate the full range of abrupt change observed in many of these  
26 periods (e.g., Valdes, 2011) and thus there is *medium confidence* (*medium evidence, medium agreement*) that these  
27 models may not capture some aspects of future climate change and associated ecosystem impacts (Leadley *et al.*,  
28 2010).

#### 29 30 31 **4.2.3. Landscapes and Social-Ecological Systems**

32  
33 Ecosystems do not exist in isolation from one another or from human systems. Landscapes, which consist of  
34 multiple interacting ecosystems, all experience some degree of interaction with people. The responses of terrestrial  
35 and freshwater ecosystems to climate change are therefore mediated by human activities at a range of spatial and  
36 temporal scales, and to varying degrees. Together, the social and ecological elements form a linked system (a  
37 'social-ecological system, SES) in which the degree of coupling can range from very close to slight (Berkes *et al.*,  
38 2003).

#### 39 40 41 **4.2.4. Multiple Stressors and the Role of Climate Change**

42  
43 While isolated effects of the main drivers of global change (e.g. climate change, habitat loss, chemical pollution and  
44 biological invasions) are increasingly well documented (Millennium Ecosystem Assessment, 2005b; Settele *et al.*,  
45 2010a) there is much less knowledge about their consequences when acting in combination. Multiple stressors can  
46 act in a non-additive way (Settele *et al.*, 2010b; Shaw *et al.*, 2002; Larsen *et al.*, 2011), potentially invalidating  
47 findings and interventions based on single-factor analysis. In a multifactorial climate change experiment Larsen *et*  
48 *al.*, (2011), demonstrated that non-additive interactions among the climate factors were frequent but most often  
49 antagonistic leading to smaller effects than predicted from the single factor effects. Leuzinger *et al.*, (2011) and  
50 Dieleman *et al.*, (2012) have synthesized such multifactor interactions and demonstrated that in general, the effect  
51 size appears to be reduced when more factors are involved. Leuzinger *et al.* (2011) further showed that models tend  
52 to show the opposite trend.

1 Climatic and non-climatic drivers of ecosystem change must be distinguished if the joint and separate attribution of  
2 changes to their causes is to be performed – of paramount importance if the processes of change are to be  
3 understood and future changes predicted. Within this section we elaborate on drivers and stressors which often act in  
4 concert with climate change, ranging from a high degree of relatedness to climate change (rising CO<sub>2</sub>; tropospheric  
5 ozone; total, diffuse and UV radiation), over intermediate (land-use change) to low degrees of relatedness (invasive  
6 species and N deposition).

#### 9 4.2.4.1. Land-Use and Cover Change (LUCC)

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

24 The cause-and-effect entanglement of climate change and LUCC make attribution of consequences to one or the  
25 other very difficult. In 13 of the 24 regional land use studies reviewed for this chapter, local-to-regional climate  
26 change was at least partly attributed to LUCC, generally with *limited evidence* and *low confidence*. (Direct climate  
27 effects attributed to LUCC: Tseng and Chen, 2008; Cui and Graf, 2009; Li *et al.*, 2009; McAlpine *et al.*, 2009;  
28 Zhang *et al.*, 2009; Fall *et al.*, 2010; Graiprab *et al.*, 2010; Jin *et al.*, 2010; Mishra *et al.*, 2010; Schwaiger and Bird,  
29 2010; Wu *et al.*, 2010; Gao and Liu, 2011; Carmo *et al.*, 2012. No climate effects attributed: Suarez *et al.*, 1999,  
30 Saurral *et al.*, 2008; SuFen *et al.*, 2008; Cochrane and Barber, 2009; Jia *et al.*, 2009a; Rounsevell and Reay, 2009;  
31 Martin *et al.*, 2010, Wiley *et al.*, 2010; Clavero *et al.*, 2011; Dai *et al.*, 2011; Viglizzo *et al.*, 2011; Yoshikawa and  
32 Sanga-Ngoie, 2011).

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

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

1 currently included in the formal rules for accounting for the climate effects of land use activities (Schwaiger and  
2 Bird, 2010; Kirschbaum *et al.*, 2012).

3  
4 The reported effects on precipitation of conversion of forest to pastures and crops vary. Many studies report rainfall  
5 decreases, soil moisture decreases and changes in rainfall pattern (e.g. Nepstad *et al.*, 2008; McAlpine *et al.*, 2009;  
6 Mendelsohn and Dinar, 2009; Eliseev and Mokhov, 2011). In some cases forest clearing has been reported to  
7 enhance local rainfall. Garcia-Carreras and Parker (2011) suggest that enhanced local precipitation can occur over  
8 deforested patches due to breezes between forest and cropland. Enhanced rainfall over vegetation boundaries has  
9 been shown to occur both in the Amazon (e.g. Knox *et al.*, 2011) and in West Africa (e.g. Garcia-Carreras *et al.*,  
10 2010) as a result of mesoscale processes that are currently not resolved in General Circulation Models.

11  
12 In China, Han *et al.*, (2012) compared historical data from 244 weather stations predominantly surrounded by  
13 cultivated land and 195 stations surrounded by with >70% natural cover. They observed a greater decrease in  
14 potential evaporation at stations with significant agricultural influence. In arid and semi-arid regions this was  
15 associated with a decrease in wind speed, increase in relative humidity and increase in air temperature compared  
16 with natural stations; while in humid and sub-humid regions it was associated with increased wind speed and  
17 decreased solar radiation.

18  
19 Several assessments conclude that LUCC, acting through habitat loss and fragmentation, is the largest cause of  
20 contemporary terrestrial and freshwater biodiversity loss, with climate change becoming an increasingly important  
21 factor later in the 21<sup>st</sup> century (Millennium Ecosystem Assessment, 2005a; <http://www.cbd.int/gbo3/>).

22  
23 \_\_\_\_\_ START BOX 4-1 HERE \_\_\_\_\_

#### 24 25 **Box 4-1. Future Land Use Pathways and Their Uncertainties**

26  
27 Assessment of climate change effects on terrestrial and inland freshwater ecosystems is incomplete in the absence of  
28 information on the direct impacts of people on these systems through land use. The world is undergoing important  
29 shifts in land-use patterns. Growth in demand for food, feed, fiber, and fuel has accelerated in recent years, placing  
30 new pressures on terrestrial and freshwater ecosystems and outpacing the growth in supply. The principal driver of  
31 this acceleration in demand is the rate at which per capita consumption is growing in emerging economies (Tilman  
32 *et al.*, 2011). Policy shifts in OECD countries favoring the expansion of biofuel production have contributed to this  
33 acceleration (Lapola *et al.*, 2010; Searchinger *et al.*, 2008; Miyake *et al.*, 2012). Growth in demand that outpaces  
34 growth in supply, climate-related crop failure (Lobell *et al.*, 2011), declines in the growth of agricultural  
35 productivity (Ray *et al.*, 2012) and possibly a shortage of arable land that is not already under cultivation, especially  
36 in the temperate zone (Lambin and Meyfroidt, 2011) are all contributing to a rise in commodity prices that may  
37 persist through 2020 (OECD/FAO, 2010) and growing pressure on as-yet uncultivated ecosystems on soils that are  
38 potentially suitable for cultivation and that are concentrated in tropical latitudes, especially South America and  
39 Africa.

40  
41 Emerging economies start from a relatively low per capita consumption base. The growth of these economies will  
42 therefore play an important role in future land use trends. Deforestation in developing countries is now correlated  
43 with the export of agricultural commodities (DeFries *et al.*, 2010), providing an early sign of the growing role of  
44 agricultural trade with emerging economies as a driver of land-use change. The trajectory of future growth in  
45 demand for land- and freshwater-based production remains uncertain, since it depends on economic trends and  
46 policies, which are themselves dependent upon complex political and social processes. One of the uncertainties  
47 about future land use trends is climate policy. Deforestation rates in the Brazilian Amazon declined 76% (as of  
48 2012) below its ten-year average as a result of policy and market signals (Soares-Filho *et al.*, 2010); this single trend  
49 represents a 1.5% reduction in global anthropogenic carbon emissions (Nepstad *et al.*, in press).

50  
51 These land use trends and the global land cover patterns that they promote have been simulated and mapped within a  
52 global grid as input to the Regional Concentration Pathways (RCPs) in preparation for the IPCC AR5. The 4 main  
53 RCPs used for future climate projections are accompanied by spatially-explicit future land use scenarios consistent  
54 with the emissions scenario and the associated socio-economic scenario (Hurtt *et al.*, 2011) generated by Integrated

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

3  
4 [INSERT TABLE 4-2 HERE

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

7  
8 In the RCPs, land cover change is driven by a number of socioeconomic drivers, including climate policy. The  
9 nature of climate policy effects on land use differs between RCPs, with some climate mitigation policy scenarios  
10 including conservation of primary vegetation (natural, mature ecosystems) as carbon sinks while others included  
11 replacement of primary vegetation with biomass and / or biofuel plantations. The extent to which primary vegetation  
12 is replaced by secondary vegetation, crops or pasture also varies between the RCPs (Figure 4-3), but there is no  
13 simple linear relationship between the extent of vegetation change and the level of total radiative forcing arising  
14 from all sources. Larger reductions in primary vegetation cover are seen in RCP8.5 (the highest emissions scenario)  
15 due to a general absence of pro-active measures to control land cover change, but large reductions were also seen in  
16 RCP2.6 (an aggressive mitigation scenario with low emissions) due to widespread conversion of land to biomass  
17 and biofuel crops coupled with carbon capture and storage. Smaller reductions were seen in RCP6.0 and RCP4.5,  
18 with the latter involving conservation of primary forest or regrowth of secondary forest as a mitigation measure.  
19 Hence both the highest and lowest emissions scenarios were associated with greater extents of land cover change.

20  
21 [INSERT FIGURE 4-3 HERE

22 Figure 4-3: Proportion of global land cover occupied by primary and secondary vegetation (forest and non-forest),  
23 cropland, pasture and urban land, from satellite data and historical reconstructions up to 2005 (KleinGoldewijk,  
24 2001), and from scenarios associated with the RCPs from 2005 to 2100 (Hurtt *et al.*, 2011).]

25  
26 Spatial patterns of the future land cover change in all RCPs were largely similar to patterns of historical change  
27 (Figure 4-4) as most future change is projected to be a continuation of past change. By definition, primary  
28 vegetation cover cannot increase on the timescales considered here, so in scenarios where cropland and pasture are  
29 projected to decrease, these are replaced with secondary vegetation. Both tropical and boreal forest regions are  
30 projected to undergo declining primary forest cover in all 4 RCPs, but in RCP6.0 total forest area remains  
31 approximately constant.

32  
33 [INSERT FIGURE 4-4 HERE

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

36  
37 \_\_\_\_\_ END BOX 4-1 HERE \_\_\_\_\_

#### 40 4.2.4.2. Nitrogen Deposition

41  
42 The global nitrogen (N) cycle has been strongly perturbed by human activity over the past century (Gruber and  
43 Galloway, 2008; Sutton *et al.*, 2011). Human activities currently transform 160 TgN/year of nitrogen gas in the  
44 atmosphere into reactive forms of N that can be readily used by plants and microorganisms in land and in the ocean  
45 (Galloway *et al.*, 2008). This is close to the pre-industrial global flux of about 255 TgN/year from all natural  
46 sources. The human-caused flow from land to the coastal oceans in rivers is about 50 TgN/y, additional to the  
47 estimated natural flux of 30 TgN/year (Galloway *et al.*, 2008). Many of the sources of additional reactive nitrogen  
48 share root causes with changes in the carbon cycle - such as increased use of fossil fuels and expansion and  
49 intensification of global agriculture - so N deposition, rising CO<sub>2</sub> concentrations and warming are increasing  
50 together at global scales (Steffen *et al.*, 2011). This large addition of reactive N into the biosphere can reinforce  
51 global warming (e.g., through emission of N<sub>2</sub>O associated with fertilizer manufacture and application), or diminish  
52 warming (e.g., by increasing C storage in many terrestrial ecosystems). The balance of these effects is difficult to  
53 estimate (Erismann *et al.*, 2011; WG1 chapter 6; Hanson *et al.*, 2005). Regional trends in N fluxes differ  
54 substantially: N fertilizer use and N deposition are stable or declining in some regions, such as Western Europe; but

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

4  
5 Experiments and observations, most of which are in temperate and boreal Europe and North America, show a  
6 consistent pattern of increase in the dominance of a few nitrogen-loving plant species and loss of overall plant  
7 species richness at N deposition loads exceeding between 5 and 20 kgN/ha/year (Bobbink *et al.*, 2010; but see  
8 Stevens *et al.*, 2010a). N deposition is currently above these limits in much of Europe, eastern North America, and  
9 Southern Asia (Galloway *et al.*, 2008), including in many protected areas (Bleeker *et al.*, 2011). Experiments  
10 examining the interactive impacts of N deposition and elevated CO<sub>2</sub> or climate change on natural systems have  
11 increased in number since the AR4, but remain few (Rustad, 2008). Recent studies show that interactions between  
12 nitrogen and other global change factors are widespread, strong and complex (Thompson *et al.*, 2008; Langley and  
13 Megonigal, 2010; Gaudnik *et al.*, 2011; Hoover *et al.*, 2012; Eisenhauer *et al.*, 2012; but see Zavaleta *et al.*, 2003a  
14 for evidence of additive effects). For example, combinations of treatments mimicking future N deposition, elevated  
15 CO<sub>2</sub> concentrations and warming had larger negative impacts on pollinator populations than could be predicted from  
16 individual treatments (Hoover *et al.*, 2012). Analyses using the multi-factor biodiversity change model GLOBIO3  
17 suggest that N deposition will continue to be a significant contributing factor to terrestrial biodiversity loss in the  
18 first third of the century but will be a less important factor than climate change in this period, and a much smaller  
19 driver than habitat loss due expansion of agricultural lands (Alkemade *et al.*, 2009). Models that explicitly take into  
20 account interactive effects of climate change and N deposition on plant communities project that N deposition  
21 impacts will continue to be important, but climate change effects will begin to dominate other factors by the middle  
22 of the 21<sup>st</sup> century (Belyazid *et al.*, 2011).

23  
24 The impacts of N deposition are often first manifested in freshwater ecosystems, since they collect and concentrate  
25 the excess N (and phosphorus) from the land, as well as from sewage and industrial effluents. Primary production in  
26 freshwater ecosystems can be either N and P limited or both (Elser *et al.*, 2007), but the biodiversity and capacity of  
27 freshwater ecosystems to deliver high quality water, recreational amenity and fisheries services is severely reduced  
28 by the addition of nutrients beyond their capacity to process them. Excessive loading of N and P is widespread in the  
29 lakes of the northern hemisphere (Bergstrom and Jansson, 2006). The observed symptoms include a shift from  
30 nitrogen limitation of phytoplankton in lakes to phosphorus limitation (Elser *et al.*, 2009).

31  
32 Since the AR4 report there has been an increase in the number of studies using models, observations and  
33 experiments to understand and predict the interactive effects of N deposition, climate change and CO<sub>2</sub> on ecosystem  
34 function. Broadly, this research shows that ecosystem function is mediated by complex interactions between these  
35 factors, such that many ecosystem responses remain difficult to understand and predict (Norby and Zak, 2011;  
36 Churkina *et al.*, 2010). For example, experiments, observations and models suggest that the observed increase in  
37 productivity and carbon storage in forests in many parts of the world is due to combinations of N deposition, climate  
38 change, fertilization effects of rising CO<sub>2</sub>, and forest management (Magnani *et al.*, 2007; Huang *et al.*, 2007; Pan *et al.*,  
39 2009; Churkina *et al.*, 2010; Bontemps *et al.*, 2011; Bellassen *et al.*, 2011; de Vries and Posch, 2011; Eastaugh  
40 *et al.*, 2011; Norby and Zak, 2011; Shanin *et al.*, 2011; Lu *et al.*, 2012). Despite difficulties in quantifying the  
41 relative contributions of these factors and their interactions, it appears that the effects of N deposition and rising CO<sub>2</sub>  
42 have generally dominated to date in much of the Northern hemisphere, however, the direct effects of rising  
43 temperature and changes in precipitation are may exceed N and CO<sub>2</sub> as key drivers of ecosystem primary  
44 productivity in a few decades time. On the other hand, experiments in grasslands show that plant productivity is  
45 increased more by N addition (within the projected range for this century) than by elevated CO<sub>2</sub>, also within its  
46 projected range; and that N effects increase with increasing precipitation (Lee *et al.*, 2010). In contrast to forests and  
47 temperate grasslands, N deposition and warming can have negative effects on productivity in other terrestrial  
48 ecosystems, such as moss-dominated ecosystems (Limpens *et al.*, 2011). The interactions between N deposition and  
49 climate change remain difficult to understand and predict (Ma *et al.*, 2011; Menge and Field, 2007), in part due to  
50 shifts in plant species composition (Langley and Megonigal, 2010) and the complex dynamics of coupled C, N and  
51 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<sub>x</sub>). Intercontinental 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<sub>3</sub> on plant productivity could offset 17% of the projected increase in global carbon storage due to increasing CO<sub>2</sub> concentrations, but the possible interactive effects between CO<sub>2</sub> and O<sub>3</sub> are poorly understood (The Royal Society, 2008). Reduced stomatal conductance widely observed under elevated CO<sub>2</sub> 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<sub>2</sub> and O<sub>3</sub> interactions in a temperate forest (Karnosky *et al.*, 2005; Hofmockel *et al.*, 2011) suggests that the effects of O<sub>3</sub> and CO<sub>2</sub> are not independent and may partly compensate for one another.

There is genotypic variation in sensitivity to O<sub>3</sub> (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<sub>3</sub> (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<sub>2</sub>

The effects of rising CO<sub>2</sub> 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<sub>2</sub> effects on plants and ecosystems has focused mainly on Free Air CO<sub>2</sub> 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<sub>2</sub>, although the response varies between species. Although FACE experiments indicate lower responses of crop yields to elevated

1 CO<sub>2</sub> than chamber studies, FACE experiments initially suggested greater biomass production of trees (Leakey *et al.*,  
2 2009). But newer results from older stands show that different system respond differently, and only at the Duke  
3 forest, a loblolly pine (*Pinus taeda*) stand in North Carolina has biomass accumulation been enhanced several years  
4 after canopy closure on rather nutrient poor soils (McCarthy *et al.*, 2010). At most other tree FACE experiments,  
5 most of the additional carbon gain has been invested into below-ground pools with short residence time, such as fine  
6 roots (Körner *et al.*, 2005; Finzi *et al.*, 2007), and the initial positive response of NPP at the Oak Ridge experiment  
7 with sweetgum (*Liquidambar styraciflua*) has disappeared due to progressive nitrogen limitation with stand  
8 development (Norby *et al.*, 2010). Acclimation (“down-regulation”) occurs under long-term exposure, leading to  
9 cessation of effects in some studies (Norby and Zak, 2011) but with on-going stimulation of photosynthetic carbon  
10 assimilation due to elevated CO<sub>2</sub> persists at a level of 19 to 46% for approximately 600 ppm CO<sub>2</sub> relative to 370  
11 ppm reported elsewhere (Leakey *et al.*, 2009). Kongstad *et al.* (2012) did not find such increases for a temperate  
12 heathland. Paleo records over the Late Quaternary also indicate effects of CO<sub>2</sub> at the ecosystem scale across the  
13 globe (Prentice and Harrison, 2009). Generally, nitrogen use efficiency and dark respiration are also both increased  
14 under higher CO<sub>2</sub> (Leakey *et al.*, 2009), but in some tree FACE experiments, productivity increases as a result of  
15 enhanced CO<sub>2</sub> were sustained by increased nitrogen uptake rather than increased nitrogen use efficiency (Finzi *et al.*,  
16 2007). Transpiration is decreased due to reduced opening of stomatal apertures which does not acclimate to higher  
17 CO<sub>2</sub> in the medium term, *i.e.* the scale of several years leading to greater water use efficiency (Leuzinger and  
18 Körner, 2010; Leakey *et al.*, 2009; De Kauwe *et al.*, 2013) – this is corroborated by additional evidence from studies  
19 of stable carbon isotopes (Barbosa *et al.*, 2010; Koehler *et al.*, 2010; Silva *et al.*, 2010; Maseyk *et al.*, 2011). C4  
20 plant species, which includes most tropical grasses and some crops, undergo photosynthesis via a different  
21 biochemical pathway which is not directly affected by elevated CO<sub>2</sub>. However, CO<sub>2</sub> rise generally increases water  
22 use efficiency of C4 plants which can exert indirect effects on growth (Leakey *et al.*, 2009). Experiments have also  
23 shown that elevated CO<sub>2</sub> has potential to stimulate root growth (e.g. Finzi *et al.*, 2007; McMurtrie *et al.*, 2012),  
24 mineralisation of soil organic matter (Drake *et al.*, 2011; Carney *et al.*, 2007, but see Finzi *et al.*, 2007) and soil  
25 microbial communities (Carney *et al.*, 2007), although Norby and Zak (2011) suggests that elevated CO<sub>2</sub> effects on  
26 the microbial community structure are minor. Impacts of CO<sub>2</sub> physiological forcing may extend beyond the  
27 organisms themselves – increased water use efficiency may significantly influence hydrological impacts (see Box  
28 CC-VW).

29  
30 Elevated CO<sub>2</sub> can assist in maintaining resilience of individual species against other stresses, such as high  
31 temperature, drought and ozone, as ozone exposure decreases with lower stomatal conductance (Sitch *et al.*, 2007).  
32 It is also suggested that faster growth rates under higher CO<sub>2</sub> can allow woody plants to become tall enough to  
33 withstand ground fires, and hence alter the fire/vegetation regime in rangelands (Bond and Midgley, 2001; Scheiter  
34 and Higgins, 2009) It is also suggested that differential species responses to elevated CO<sub>2</sub> are altering competition  
35 (Dawes *et al.*, 2011), for example, increasing the likelihood of faster-growing species such as lianas out-competing  
36 slower-growing species such as trees (Potvin *et al.*, 2007; Lewis *et al.*, 2009a).

37  
38 The interactive effects of elevated CO<sub>2</sub> and other global changes (such as climate change, nitrogen deposition and  
39 biodiversity loss) on ecosystem function are extremely complex and as yet poorly predictable (Potvin *et al.*, 2007).  
40 For example, in one ten-year temperate grassland experiment in Minnesota, elevated CO<sub>2</sub> halved the loss of species  
41 richness due to nitrogen addition (Reich, 2009), whereas no such change was reported for a similar experiment in  
42 annual grassland on serpentine soils in California (Zavaleta *et al.*, 2003a) or an alpine grassland in France (Bloor *et al.*,  
43 2010) or a Danish heathland ecosystem (Kongstad *et al.*, 2012). Some of the mechanisms of community and  
44 production changes under multi-factor forcing may be mediated through changes in plant litter quality, although in  
45 the temperate grassland experiment described above the changes in litter decomposition rates were less marked than  
46 the changes in the chemical composition of tissues (Knops *et al.*, 2007). Hyvönen *et al.* (2007) review the combined  
47 effects of elevated CO<sub>2</sub>, temperature, nitrogen deposition and management on carbon sequestration in temperate and  
48 boreal forests and conclude that findings extrapolated from experiments that only consider one of these factors in  
49 isolation can be misleading. Since FACE experiments either examine CO<sub>2</sub> effects in isolation, or in conjunction with  
50 a very limited set of imposed climate changes such as elevated temperature, the extent to which CO<sub>2</sub> responses are  
51 affected by a range of temperature changes or other climatic or environmental factors remains poorly studied. A  
52 further, broader analysis supports this, and further suggests that the magnitude of CO<sub>2</sub> effects decreases as the scale  
53 of study increases (Leuzinger *et al.*, 2011).



1 Inclusion of CO<sub>2</sub> effects can be a first-order influence on model projections of ecosystem and hydrological responses  
2 to anthropogenic climate change. For example, most CMIP3 climate models project a drying, warming trend in  
3 Amazonia, and this leads to widespread forest loss being simulated under most climate projections in a model that  
4 ignores CO<sub>2</sub> effects (Salazar *et al.*, 2007). However, when CO<sub>2</sub> effects are included, the same model projects forest  
5 loss under fewer climate projections (Lapola *et al.*, 2009). The current generation of dynamic global vegetation  
6 models (DGVMs; (Sitch *et al.*, 2008), which includes those used within the CMIP5 Earth System Models, uses  
7 formulations based on experimental work that pre-dates FACE experiments (e.g., Farquhar *et al.*, 1980; Collatz *et*  
8 *al.*, 1992). However, the DGVMs simulate present-day global carbon budgets that agree with those inferred from  
9 observations such as the atmospheric CO<sub>2</sub> record (Sitch *et al.*, 2008).

10  
11 The effect of CO<sub>2</sub> on plant physiology independent of its role as a greenhouse gas has implications for the definition  
12 of “dangerous climate change” in terms of levels of global mean temperature rise, and for the use of “CO<sub>2</sub>  
13 equivalent” metrics for comparing different greenhouse gases. Aside from uncertainties in the response to a given  
14 change in CO<sub>2</sub> concentration, the relative importance of radiative forcing and “CO<sub>2</sub> physiological forcing” depend  
15 on uncertainties in the response of global climate to radiative forcing and also on the relative proportions of CO<sub>2</sub> and  
16 other greenhouse gases (Betts *et al.*, 2012). The impacts of, for example, a 2°C rise in global mean temperature may  
17 have a very different net impact on ecosystems depending on the change in CO<sub>2</sub> concentration accompanying this  
18 rise. A high climate sensitivity and/or a higher proportion of non-CO<sub>2</sub> GHGs would imply a relatively low CO<sub>2</sub> rise  
19 at 2°C global warming, so the offsetting effects of CO<sub>2</sub> fertilization and increased water use efficiency would be  
20 smaller than for low climate sensitivity and/or a lower proportion of non-CO<sub>2</sub> GHGs. Similarly, inertia in the climate  
21 system means that warming would be expected to continue for many decades after stabilisation of GHG  
22 concentrations, so the relative contribution of CO<sub>2</sub> physiological effects would diminish over time. Comparison of  
23 the effects of CO<sub>2</sub> with other GHGs in terms of the current radiative forcing-based metrics may therefore not be  
24 representative of the relative effects of different GHGs on ecosystems and hydrology (Huntingford *et al.*, 2011).

25  
26 There remain still important limitations on understanding of CO<sub>2</sub> responses. Large-scale FACE experiments have  
27 still only been conducted for up to two locations for any particular ecosystem type, and these are in temperate and  
28 boreal regions (e.g. Hickler *et al.*, 2008); there is currently no tropical FACE experiment. The scale of controlled  
29 experiments is limited to approximately 100m<sup>2</sup>, and extrapolation to larger scales may not be appropriate as other  
30 constraints may be important, for example large-scale atmospheric feedbacks (Körner *et al.*, 2007). Similarly, the  
31 limited size of FACE experiments means that influences on catchment-scale hydrology have not yet been studied  
32 experimentally. The majority of FACE experiments examine CO<sub>2</sub> concentrations of approximately 550 ppmv),  
33 which has been projected to be reached by the end of the 21<sup>st</sup> Century under a number of scenarios including  
34 RCP6.0 (van Vuuren *et al.*, 2011), whereas higher concentrations are projected under higher emissions scenarios;  
35 RCP8.5 reaches a CO<sub>2</sub> concentration of approximately 900 ppmv by 2100 (van Vuuren *et al.*, 2011). However, the  
36 basic physiology of photosynthesis suggest that CO<sub>2</sub> effects saturate at levels of approx. 700 ppmv (Long *et al.*,  
37 2004). Moreover, FACE experiments impose a sudden increase of CO<sub>2</sub> concentration as opposed to the continuous  
38 rise measured in the present-day atmosphere. The extent to which photosynthesis and nitrogen and water use  
39 efficiency continue to increase with ongoing CO<sub>2</sub> rise therefore remains poorly-constrained. Overall, there is  
40 *medium confidence (much evidence, medium agreement)* that increases in CO<sub>2</sub> up to about 600 ppm will continue to  
41 enhance photosynthesis and plant water-use efficiency, but at a diminishing rate

#### 42 43 44 4.2.4.5. Diffuse Versus Direct Radiation

45  
46 The quantity and size distribution of aerosols in the atmosphere alters both the amount of solar radiation reaching  
47 the Earth’s surface and its distribution between direct and diffuse radiation. There are observed trends in diffuse and  
48 direct radiation in many parts of the world, usually in the direction of overall ‘dimming’. Locally, direct radiation is  
49 reduced by up to 30 W m<sup>-2</sup>, with an accompanying increase in diffuse radiation of up to 20 W m<sup>-2</sup> (Kvalevåg and  
50 Myhre, 2007). The global mean direct and diffuse radiation changes due to aerosols are -3.3 and +0.9 W m<sup>-2</sup>,  
51 respectively (Kvalevåg and Myhre, 2007). For a constant total radiation, an increased fraction received as diffuse  
52 radiation theoretically increases net photosynthesis, (Knobl and Baldocchi, 2008; Kanniah *et al.*, 2012) and  
53 potentially could alter the hydrological balance and soil temperature. In a global model which included this process,  
54 an increase in diffuse fraction of solar radiation due to volcanic and anthropogenic aerosols and cloud cover was

1 simulated to lead to approximately a 25% increase in the strength of the global land carbon sink between 1960 and  
2 1999; but under a scenario of climate change and decreased anthropogenic aerosol concentration, this enhancement  
3 declined to near zero by the end of the 21<sup>st</sup> Century (Mercado *et al.*, 2009). The influence of form of radiation on  
4 plant growth and the land carbon budget is a potentially important unintended consequence of solar radiation  
5 management schemes that involve the injection of aerosols into the stratosphere to reduce radiant forcing (Boucher  
6 *et al.*, in preparation) but is presently insufficiently researched for adequate assessment.

#### 7 8 9 4.2.4.6. *Invasive and Alien Species*

10  
11 Since the IPCC AR4, the number of observations of the spread and establishment of alien species attributed to  
12 climate change has increased for several taxa (e.g. Walther *et al.*, 2009) and for particular areas, including mountain  
13 tops and polar regions (McDougall *et al.*, 2011; Chown *et al.*, 2012). The aggressive expansion of plant and animal  
14 species beyond their historical range is having increasingly negative impacts on ecosystem services and biodiversity  
15 (*high confidence*; Brook, 2008; Burton *et al.*, 2010; McGeoch *et al.*, 2010; Simberloff *et al.*, 2013). Climate change  
16 will exacerbate some invasion impacts and ameliorate others (Peterson *et al.*, 2008; Bradley *et al.*, 2009; Britton *et al.*,  
17 2010). The spread of alien species has several causes, including habitats made favorable by climate change  
18 (Walther *et al.*, 2009), deliberate species transfer and accidental transfer due to increased global movement of goods.

19  
20 In most cases climate change increases the likelihood of the establishment, growth, spread and survival of invasive  
21 species populations (Dukes *et al.*, 2009; Walther *et al.*, 2009; Bradley *et al.*, 2010; Huang *et al.*, 2011; Chown *et al.*,  
22 2012). However, divergent alien species responses and local consequences are expected (e.g. Rahel and Olden,  
23 2008; Frelich *et al.*, 2012; Haider *et al.*, 2012; West *et al.*, 2012). Invasive species compared to native species might  
24 have traits that favor their survival, reproduction and adaptation under changing climates; invasive plants in  
25 particular tend to have faster growth rates and are particularly favored when resources are not limited (*medium to*  
26 *high confidence*; Buswell *et al.*, 2011; Davidson *et al.*, 2011; Zerebecki and Sorte, 2011; van Kleunen *et al.*, 2010;  
27 Willis *et al.*, 2010a; Haider *et al.*, 2012; Matzek, 2012). Invasive plants tend to be more drought tolerant (Crous *et al.*,  
28 2012; Matzek, 2012; Perry *et al.*, 2012), and on average have higher overall metabolic rates, foliar nitrogen  
29 concentrations and photosynthetic rates than their native counterparts (Leishman *et al.*, 2007).

30  
31 Extreme climate events may provide opportunities for invasion by generating disturbances and resource pulses (Diez  
32 *et al.*, 2012). Current warming has already enabled many alien species, including plant, vertebrate, invertebrate and  
33 single cell taxa, to extend their distributions into new areas (*high confidence* for plants and insects; Walther *et al.*,  
34 2009; Smith *et al.*, 2012). Population declines and range contractions are however predicted for some invasive  
35 species in parts of their ranges (Bradley *et al.*, 2009; Bertelsmeier *et al.*, 2012; Sobek-Swant *et al.*, 2012; Taylor *et al.*,  
36 2012;). The expansion of invasive species in some areas and contraction in others will contribute to community  
37 re-organisation and the formation of novel ecosystems and interactions in both terrestrial and freshwater habitats  
38 (*high confidence*; e.g., Kiesecker, 2011; Britton *et al.*, 2010; Martinez, 2012; see also chapter 4.3.2.5.). For example,  
39 invasive grasses will probably be favored over native ones with increasing temperatures (Parker-Allie *et al.*, 2009;  
40 Chuine *et al.*, 2012; Sandel and Dangremond, 2012).

41  
42 Benefits to biodiversity and society as a result of interactive effects of climate change and invasive species will be  
43 experienced in individual cases, such as increases in resources available to some threatened species (Caldow *et al.*,  
44 2007), forest structural recovery (Bolte and Degen, 2010) and available biomass for timber and fuel (van Wilgen and  
45 Richardson, 2012). The effect of invasions on net changes in carbon stocks are situation specific, and may be either  
46 positive or negative (Williams *et al.*, 2007a). Rising CO<sub>2</sub> levels will increase the growth rates of most invasive plant  
47 species (Mainka and Howard, 2010), but the effectiveness of invasive species management for sequestering carbon  
48 is uncertain and context specific (Peltzer *et al.*, 2010). Longer term, indirect effects of invasive species will be more  
49 important than direct, short-term effects, as a result of changes in soil carbon stocks and tree community  
50 composition (*low-medium confidence*; Peltzer *et al.*, 2010).

51  
52 Threat syndromes are formed by synergistic interactions between climate change and invasive species, along with  
53 landscape change, habitat disturbance and human-facilitated breakdown of dispersal barriers (Brook, 2008; Angeler  
54 and Goedkoop, 2010; Bradley *et al.*, 2010; Winder *et al.*, 2011; Cahill *et al.*, 2013). Climate change and invasive

1 species change the risk and properties of fire, and the interaction is being reported more frequently as a direct result  
2 of higher temperatures and increased invasive plant biomass (*high confidence*; Abatzoglou and Kolden, 2011). In  
3 freshwater systems, alien species establishment and survival, species interactions and disease virulence will change  
4 as a result of changes in frequency of high-flow events, increasing water temperature, water properties and water  
5 demand (*medium confidence*; Schnitzler *et al.*, 2007; Rahel and Olden, 2008; Britton *et al.*, 2010).  
6

7 A range of climate change-related variables (extreme events, changes in precipitation, temperature and CO<sub>2</sub>) will  
8 continue to exacerbate the establishment and spread of pests, vectors and pathogens and negatively impact on crop  
9 production (*medium confidence*; Robinet and Roques, 2010; Clements and Ditommaso, 2011). Warming has led to  
10 the spread of many invasive insect species such as the mountain pine bark beetle and resulted in forest destruction  
11 (*high confidence*; Kurz *et al.*, 2008). The interactions between crop growth, climate change and pest dynamics are  
12 however complex to predict (West *et al.*, 2012). Management strategies may become less effective as a consequence  
13 of decoupling of biocontrol relationships and less effective mechanical control as biomass of invasive species  
14 increases (*low to medium confidence*; Hellmann *et al.*, 2008).  
15  
16

### 17 **4.3. Vulnerability of Terrestrial and Freshwater Ecosystems to Climate Changes**

  
18

19 Vulnerability of terrestrial ecosystems to climate change is defined as the combination of three things: the degree to  
20 which their climatic environment changes relative to conditions under which the ecosystem evolved; the sensitivity  
21 of ecosystem processes to the elements of climate undergoing change; and the degree to which the system (including  
22 its coupled social elements) can maintain its structure, composition and function in the presence of such change,  
23 either by tolerating the change or adapting to it. See WGII chapter 19 for a fuller discussion on vulnerability  
24 concepts.  
25  
26

#### 27 **4.3.1. The Importance of Changes in Disturbance Regime**

  
28

29 The species composition at a given location is determined by three factors: the physiological tolerance of the various  
30 species that have access to the site in relation to the range of conditions experienced there; interactions with other  
31 species, including competitors, symbionts, predators, prey and pathogens; and the ability of species to reach the  
32 location in evolutionary or recent times. Occasional disturbances that relieve competition and create opportunities  
33 for establishment and success of less-dominant species are important in maintaining diversity. The average  
34 environmental conditions are often less of a determinant of species ranges than the extremes, such as the occurrence  
35 of exceptionally cold or hot days or droughts exceeding a certain duration, which are often defined as ‘disturbances’.  
36 The change in probability of such extremes is typically disproportionately larger than the change in the mean (see  
37 IPCC, 2012, but also Diffenbaugh *et al.*, 2005). Fire, floods and strong winds are all examples of biodiversity-  
38 sustaining events, provided that their frequency and intensity does not deviate greatly from the regime that prevailed  
39 at the location in evolutionary time; outside this range they have adapted to (Connell, 1978).  
40

41 It is thought that widespread compositional shifts resulting from climate change in interaction with other factors will  
42 often be associated with changes in the disturbance regime, rather than physiological tolerance (Thonicke *et al.*,  
43 2008). A ‘disturbance regime’ refers to the totality of different types of disturbance events in a system, each  
44 characterized by their probability-intensity function and other relevant attributes, such as their seasonal distribution.  
45 A corollary is that disturbance-related change is likely to abrupt rather than gradual.  
46

47 Change in the fire disturbance regime, in particular, is emerging as a key, mechanism of terrestrial ecosystem  
48 change and an early indicator of change that has been detected and in some cases attributed to climate change  
49 (Westerling *et al.*, 2006; Littell *et al.*, 2009; Westerling *et al.*, 2011; Moritz *et al.*, 2012).  
50  
51  
52

### 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 21<sup>st</sup> 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<sub>2</sub> 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<sub>2</sub> concentrations are contributing to this trend through stimulation of photosynthesis, but there is no clear, consistent signal of a climate change contribution.

1 *Evapotranspiration (see 4.3.2.4)* - Evapotranspiration is now being monitored at a variety of scales ranging from  
2 individual plants to large regions. A variety of studies suggest that evapotranspiration increased over the period  
3 1970-1990, but there is substantial uncertainty in this estimate due to low agreement across studies leading to *low*  
4 *confidence* in detection of a trend. The trend of rising evapotranspiration from 1970-1990 has been attributed to  
5 global warming, and the absence of a continued trend in from the 1990s onward has been attributed to increased  
6 water stress. However, there is *low confidence* in these attributions because of the large number of confounding  
7 factors that influence transpiration including N deposition, land management and irrigation.

8  
9 *Species Distributions (see 4.3.2.5)* - Depending on the species and species group, there are varying degrees of  
10 confidence in the detection of species range shifts and that these range shifts can be attributed to climate change.  
11 The number of species studied has considerably increased since the AR4 report as have the number of studies  
12 examining the mechanisms underlying range shifts. There is a wide range of evidence from models, field studies,  
13 and quantitative comparisons between observed and expected range shifts that some species and species groups,  
14 especially arthropods, have shifted their ranges significant distances (10s of km or more) over the last several  
15 decades (*high confidence*). Range shifts — that must be distinguished from shifts in community composition — in  
16 other key species groups such as plants have been much more difficult to detect, meaning there is only *medium*  
17 *confidence* in detection in range shifts when examined across all species groups. Range shifts in some species  
18 groups, e.g., arthropods, correlate well with warming over the last several decades and can be linked to changes in  
19 climate through understanding of mechanisms. But for many other species groups range shifts are more difficult to  
20 attribute to changes in climate because the climate signal is small, there are many confounding factors, differences  
21 between expected and observed range shifts are large, or variability within or between studies is high. Thus there is  
22 only *medium confidence* in attribution when examined across all species. An importance advance since the AR4  
23 report is the recognition changes in climate over the last several decades have led to range shifts that are frequently  
24 not towards the poles or up in altitude due to many factors including interactions between warming, land use and  
25 changes in precipitation (*high confidence*).

26  
27 *Global Species Extinctions (see 4.3.2.5)* - There is *high confidence* that global species extinctions are at or above the  
28 highest rates of species extinction in the fossil record, and *high confidence* that global extinctions have increased in  
29 some species groups, e.g., amphibians, over the last several decades. However, across all taxa there is only *low*  
30 *confidence* that rates of species extinctions have increased over the last several decades. Only a small fraction of  
31 observed species extinctions have been attributed to climate change — most have been ascribed to invasive species,  
32 overexploitation, habitat loss or habitat modification. As such, there is *very low confidence* that observed species  
33 extinctions can be attributed to recent climate warming given the small fraction of species for which global  
34 extinction has been ascribed to climate change and tenuous nature of most attributions. However, in the specific case  
35 of Central American amphibians, there is *medium evidence* that recent climate warming has contributed to  
36 extinctions and *medium confidence* in this attribution. There is *low agreement* among investigators concerning the  
37 importance of climate compared to other factors such as invasive disease and habitat loss.

38  
39 *Invasive and Alien Species (see 4.2.4.6)* - There is *very high confidence* that species invasions are increasing over the  
40 last several decades. There is *high confidence* that recent climate trends have contributed to the establishment,  
41 growth, spread and survival of some alien species populations in some regions, but only *low confidence* that the  
42 species invasions have generally been assisted by recent climatic trends because of the overwhelming importance of  
43 human facilitated dispersal in mediating invasions.

44  
45 *Tree Mortality (see 4.3.3.1, Box 4-2)* - Extensive tree mortality appears to be increasing globally, but there is *low*  
46 *confidence* in detection due to a lack of temporal and spatial coverage of tree mortality. In particular, the increase in  
47 reporting of mortality may reflect greater observation effort rather than a real increase in mortality. In many cases,  
48 tree mortality can clearly be linked directly to climate impacts, especially heat and drought. However, attribution to  
49 directional climate change over the last several decades is difficult (*low confidence*) due to lack of time series  
50 measurements for a large range of forested systems and the large number of confounding factors mediating tree  
51 mortality.

52  
53 *Boreal Forest Regime Shift (see 4.3.3.1.1, Box 4-4)* - An increase in tree mortality is observed in many boreal  
54 forests, with particularly widespread dieback related to insect infestations in North America. Tree health in boreal

1 forests varies greatly among regions, which coupled with insufficient temporal coverage means that there is *low*  
2 *confidence* in the detection of a clear temporal trend in mortality at the global scale. Models and paleobotanical data  
3 indicate that regression of boreal forest at its southern edge is a predictable response to warming. High magnitudes  
4 of climate change over most of boreal forest also facilitate attribution to global warming. In some cases, tree  
5 mortality can be linked directly or indirectly (e.g., due to changes in insect and pathogen ranges) to fluctuations in  
6 climate. However, the lack of long-term data sets and high spatial heterogeneity means that attribution to climate  
7 change is of *low confidence*.

8  
9 *Amazon Forest Regime Shift* (see 4.3.3.1.3, Box 4-3) - Long-term increases in tree turnover (increased mortality and  
10 growth) in the humid tropical forests of the Amazon basin have been documented with *moderate confidence*. In  
11 addition, two episodes of extreme drought over the last decade have led to increased mortality of large trees. There  
12 is *low confidence* that this represents a trend towards degradation of humid tropical forest, since structural changes  
13 in intact forests have been minor. Observed changes in tree turnover have been ascribed to a variety of mechanisms  
14 including rising CO<sub>2</sub> effects on vines, recovery from past disturbance and changing climate; the attribution to these  
15 various drivers is difficult due to limited temporal and spatial coverage. Models and experiments lend credence to a  
16 contribution of climate to increased tree mortality and growth. There is *very low confidence* in attribution of  
17 observations to climate change because of the short period of intensive monitoring records and because warming  
18 trends over the last several decades are weak in this region.

19  
20 *Tundra Regime Shift* (see 4.3.3.4) - Field and satellite measurements indicate an increase in shrub growth and  
21 permafrost thawing in many areas of the Arctic tundra. Lack of temporal coverage makes it difficult to know if this  
22 is a strong directional signal leading to *medium confidence* in detection of a trend. It is not clear to what extent this  
23 presages boreal forest encroachment into tundra, which would have much larger impacts on ecosystem structure and  
24 function. Experiments, models and paleontological responses of tundra to past warming all indicate that the increase  
25 in shrub coverage and permafrost thawing are predictable responses to climate warming trends. High magnitudes of  
26 climate change over the last 50 years for most of the Arctic facilitate attribution. The lack of long-term monitoring  
27 data makes it difficult to attribute these changes to climate change with greater than *medium confidence*.

28  
29 *Cultural Landscapes* (see 4.3.3.5) - There is *very high confidence* that species composition and landscape structure  
30 are changing in cultural landscapes such as Satoyama landscapes in Japan or mixed forest, agricultural landscapes in  
31 Europe. Models and experiments suggest that climate change should be contributing to these observed changes. The  
32 land use and land management signal is so strong in these landscapes, that there is *very low confidence* that we can  
33 attribute these observations to climate change.

34  
35 *Evolutionary and Genetic Adaptation* (see 4.4.1.2) - While there are an increasing number of observations of "rapid  
36 evolutionary" responses to climate variation, the number of species studied is extremely limited. In addition, it  
37 remains difficult to separate phenotypic from genotypic adaptation meaning that there is only *low confidence* that we  
38 are detecting a widespread signal of evolutionary or genetic adaptation to climate. An increasing number of models  
39 and experiments illustrate that "rapid evolutionary" responses are possible and even probable response to climate  
40 change. In a few cases, strong correlations between climate trends and changes in gene frequencies underlying  
41 phenological responses to climate trends suggest that climate change is an important driver of rapid evolution. The  
42 limited number of well-studied cases means there is only *low confidence* in attribution of adaptation as a generalized  
43 response to changes in climate over the last several decades.

#### 46 4.3.2.1. Phenology

47  
48 A large number of site-specific studies, and more recently satellite imagery, allow monitoring of phenology. The  
49 advance in spring events (e.g. breeding, bud burst, breaking hibernation, flowering, migrating,) has been reported for  
50 many regions, especially from the northern hemisphere but fewer in the southern hemisphere and for many plant and  
51 animal taxa. Since the AR4 many new studies showing phenological adaptations of species as response to climate  
52 change (e.g., amphibians: Kusano and Inoue, 2008; birds: Pulido, 2007; Thorup *et al.*, 2007; mammals: Adamik and  
53 Kral, 2008; Lane *et al.*, 2012; plants: Cleland *et al.*, 2007; Gordo and Sanz, 2009; plants and animal taxa: Høye *et*  
54 *al.*, 2007; Primack *et al.*, 2009) and meta analyses were published (observed data: Parmesan, 2006; Parmesan, 2007;

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

3  
4 Large-scale changes and variations in vegetation have been monitored by satellite since 1982 (White *et al.*, 2009).  
5 The Advanced Very High Resolution Radiometer (AVHRR) quantifies the differences in visible and near-infrared  
6 wavebands of outgoing radiation (NDVI) which is related to the quantity of photosynthetically-active vegetation.  
7 The times of maximum and minimum rate of change of NDVI provide a metric of the growing season. From 1982 to  
8 2008 the NDVI-defined start of the growing season advanced by 5.4 days at the hemispheric scale, and the end was  
9 delayed by 6.6 days (Jeong *et al.*, 2011). Rates of change varied over time and at smaller scales. Changes were  
10 found to be strongly related to temperature trends, although changes in precipitation may also be key drivers,  
11 especially in more arid regions (McPherson, 2007). Studies with the more recent instrument, Moderate Resolution  
12 Imaging Spectrometer (MODIS), and other metrics such as Leaf Area Index (the ratio of leaf area to ground area;  
13 Ahl *et al.*, 2006) provide a similar picture at large scales, although results can differ at local scales due to the use of  
14 different instruments, indices and trend detection methods. The relatively short duration of satellite observations  
15 makes trend detection particularly sensitive to the choice of analysis period. Nevertheless, the general emerging  
16 picture of an advancement of the start of the growing season length is consistent with ground-based phenology  
17 studies. At a regional scale, a combination of species-level observations, meta-analysis, NDVI measurements and  
18 phenology modeling to reveal geographically different advancements in spring phenology of Chinese plant  
19 communities in different Ecoregions and Biomes between the 1960s and 2000s (Ma and Zhou, 2012 ).

20  
21 Changes in breeding phenology are reported from various regions and different taxa (insects, birds, mammals,  
22 amphibians; e.g. Parmesan, 2006; Parmesan, 2007; Post *et al.*, 2008; Primack *et al.*, 2009). Various factors can be  
23 attributed to changes on breeding phenology, e.g. food availability, increasing spring temperatures. In the northern  
24 hemisphere several studies show advancements of egg laying dates in birds (e.g. Parmesan, 2007: -3.70 days/decade  
25  $\pm 0.7$ , n= 41 species in a meta-analysis). In mammals, Réale *et al.* (2003) found for the female North American  
26 squirrel (*Tamiascurus hudsonicus*) an advancement of 18 days of the mean parturition day in 10 years (1992-2002)  
27 in the Yukon area, Canada, coinciding with increasing abundance of white spruce cones, the major food source. For  
28 the southern hemisphere the opposite pattern, a significant delay of the mean breeding date by 2.8 to 3.7 days  
29 between 1950 and 2004 for two of nine seabirds in the Eastern Antarctic (Barbraud and Weimerskirch, 2006).

30  
31 Patterns of changes in autumn migration in birds are mostly not consistent (delayed, advanced, no change) across  
32 analyzed species and regions and appear to be highly related to non-climatic variables (e.g. Sokolov, 2006; Adamik  
33 and Pietruszkova, 2008). Phenological response can differ with migration strategy in birds, such as short distant  
34 migrants show greater advancements in spring arrivals than long distant migrants (e.g. Saino *et al.*, 2009; but see  
35 Parmesan, 2006 for different patterns). Insects show also a variety of phenological responses to changing  
36 temperatures (e.g. reviewed in Robinet and Roques, 2010). Development rates speed up and for polyvoltine species  
37 an increase in number of generations attributed to increasing temperatures and a lengthening of the growing seasons  
38 due to earlier timing of last winter frost and later timing of first fall frosts) are reported (e.g. Menzel *et al.*, 2003;  
39 Kunkel *et al.*, 2004; Sunley *et al.*, 2006; Robinet and Roques, 2010)

40  
41 A variety of environmental drivers could affect behavioral changes in species. Experimental-manipulation shows  
42 that higher temperatures lead to significantly earlier egg laying dates of the great tit (*Parus major*) in 5 out of 6 years  
43 (Visser *et al.*, 2009), but rates of seasonal warming may also be important (Schaper *et al.*, 2012). In a temperate  
44 region (Massachusetts, USA), declining sizes of migration cohorts or of populations appeared to account for a large  
45 amount of the variation in previously documented changes in migration times between 1970 and 2002 (Miller-  
46 Rushing *et al.*, 2008). After accounting for changes in migration cohort size, migration distance, climatic variables,  
47 and migration date explained portions of the variation in migratory changes over time. Changes in migration  
48 phenology cannot only be attributed to changes in temperature changes but also to differing variability of changed  
49 feathers during moulting times, food availability at stop-over places and differing health conditions of individual  
50 species (Gordo, 2007).

51  
52 Snow cover and snow depth can also be important factors. Interactions between temperature precipitation  
53 determining snowmelt changes, which is reported to lead to earlier flowering and appearances of plants and  
54 arthropods in Greenland between 1996 and 2005 (Høye *et al.*, 2007) and earlier flowering in an alpine plant in the

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

8  
9 Experiments are an important source of information on physiological and phenological responses to changing  
10 climate, but some caution should be exercised when translating their results into future projections using models.  
11 Wolkovich *et al.* (2012), in a large meta-analysis, suggested that warming experiments substantially  
12 underpredict advances in the timing of flowering and leafing of plants. They also showed that experimentally-  
13 derived temperature sensitivities of species did not match the observations in the wild. However, in contrast,  
14 Gunderson *et al.* (2012) found good agreement between experimental warming and *in situ* observations.  
15 Experiments on wild species may also directly affect results; for example, flipper-tagging of penguins can alter their  
16 migratory behavior (Saraux *et al.*, 2011).

17  
18 Generally, there is a great interspecific variability in phenological responses to changing climatic factors (e.g.:  
19 Gunderson *et al.*, 2012). Changes in interspecific interactions, such as predator-prey or interspecific competition for  
20 food, stemming from changes in phenological characteristics and breakdown in synchrony between species have  
21 been observed. Parmesan (2007) found taxonomic groups to be advancing at significantly different rates, with  
22 amphibian breeding date advancing by eight times as much as other groups, birds and butterflies were not  
23 significantly different from each other, but both showed spring advancement three times stronger than for herbs and  
24 grasses. Since most butterfly species eat herbs and grasses as host plants, this suggests an increasing asynchrony  
25 between these two interacting groups. Thackeray *et al.* (2010) draw similar conclusions. Species unable to adjust  
26 their behavior, i.e. advancement of spring events to keep track with changing climates could be negatively affected.  
27 This may be particularly important in highly seasonal habitats (Both *et al.*, 2010). The degree, direction and strength  
28 of the asynchrony due to changing climatic variables depends on differences in the phenology of the interacting  
29 species (van Asch and Visser, 2007). Increasing temperatures may either bring species more into synch or more out  
30 of synch, depending on their respective starting positions (Singer and Parmesan, 2010), although evidence is more  
31 towards a loss of synchrony (Visser and Both, 2005). Changes in (a)synchrony of interacting species is assumed to  
32 effect dynamical features of ecological communities such as trophic cascades, competitive hierarchies, and species  
33 coexistence (Nakazawa and Doi, 2012). Ahola *et al.* (2007) could show that the competition between the resident *P.*  
34 *major* and the migratory pied flycatcher (*Ficedula hypoleuca*) is increasing when the onset of breeding of both is  
35 becoming closer to each other and the abundances of both species are increasing (data: 1953–2005; South-Western  
36 Finland). This pattern resulted in a relative host change to more long-distant hosts. van Asch and Visser (2007)  
37 report increasing asynchrony of the winter moth (*Operophtera brumata*) and its feeding host oak tree (*Quercus*  
38 *robur*) due to increasing spring temperatures and not changing winter temperatures (based on a descriptive model,  
39 oak data: 1975–1999, Netherlands, moth data: 1995–1999; Oosterhout, Warnsborn, Doorwerth, Arnhem;  
40 Netherlands). The edible dormouse (*Glis glis*), a nest predator advanced its hibernation termination significantly  
41 with -8 days per decade in the Czech Republic between 1975–2005 due to increasing annual spring air temperatures,  
42 leading to increased nest predation in three out of four bird surveyed species (Adamik and Kral, 2008)

43  
44 Cross taxa observations show high variation in species- and location specific responses to increasing temperatures in  
45 both direction and magnitude (e.g. Parmesan, 2007; Primack *et al.*, 2009; Thackeray *et al.*, 2010). Uncertainties and  
46 biases can be introduced in research that compares different taxonomic groups or geographic regions by often  
47 incomplete or non-overlapping time series, averaged geographical scales, lack of consideration of effects of local  
48 climatic variability (e.g. wind speed, climatic conditions at stop-over places) and mostly unknown pressures in  
49 winter ranges for migratory species (Hudson and Keatley, 2010). With too short time series long term trends in  
50 phenological changes cannot be detected, although responses to annual climate variability can often be  
51 characterized. However, some studies now extend over several decades (Cook *et al.*, 2008) or even 100 years (Naef-  
52 Daenzer *et al.*, 2012). Given the geographical coverage and length over time over which studies are now available,  
53 there is high confidence (*robust* evidence, high agreement) that phenological shifts are occurring as a response to a  
54 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  $2.6 \pm 0.7$  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

1 changes in the environment to which the tree was exposed. Variations in tree ring parameters arise from many  
2 factors, including temperature, moisture stress, CO<sub>2</sub> fertilization and ozone damage. The most recent rings in most  
3 published tree ring chronologies date from before the 1990s (Gedalof and Berg, 2010) so tree ring-based conclusions  
4 for more recent dates are based on a smaller body of evidence. Sites which are not sensitive to environmental  
5 changes may therefore be under-represented. Direct repeated measurements of tree girth increment in forest  
6 monitoring plots (discussed in 4.3.2.3) are an alternate data source for recent decades. Tree ring studies may not be  
7 representative of forests in general, as most studies were specifically designed to examine growth in response to  
8 environmental changes (Gedalof and Berg, 2010).  
9

10 Many tree ring records show a tendency of accelerated tree growth during much of the 20th century (Briffa *et al.*,  
11 2008), which often correlates with rising temperature. Direct CO<sub>2</sub> effects, inferred from the ring record once the  
12 effects of drought and temperature have been accounted for, have been proposed for approximately 20% of the sites  
13 in the International Tree Ring Data Base (Gedalof and Berg, 2010) and studied in detail at some sites (Koutavas,  
14 2008). Since the 1980s a number of tree ring records show a decline in tree growth (Wilson *et al.*, 2007). Several  
15 possible causes have been suggested for this, including increasing water stress and ozone damage.  
16

#### 17 4.3.2.3. Biomass and Carbon Stocks

18 Forests are routinely monitored for management and research purposes, typically by recording species composition  
19 and stem size distribution in hundreds of small plots. Forest carbon stock can be estimated from this and forest area  
20 data, usually derived from remote sensing. Repeated forest inventories in principle allow the growth rate and change  
21 in carbon stock to be estimated. Forest inventories were designed to track timber volumes; inferring total biomass  
22 and ecosystem carbon stocks requires further information and assumptions, which make absolute values less certain,  
23 but have a lesser effect on trend detection. Forest inventory systems are well-developed for northern hemisphere  
24 temperate and boreal forest (Nabuurs *et al.*, 2010; Ryan *et al.*, 2010; Wang *et al.*, 2010a). Data for tropical and  
25 southern hemisphere forests and woodlands also exist (Maniatis *et al.*, 2011; Tomppo *et al.*, 2010) but are typically  
26 less available and comprehensive (Romijn *et al.*, 2012). More and better data may become available due to advances  
27 in remote sensing (e.g. Baccini *et al.*, 2012) and the REDD+ initiative.  
28

29 Forests have increased in biomass and carbon stocks over the past half century in Europe (Ciais *et al.*, 2008;  
30 Luyssaert *et al.*, 2010) and the USA (Birdsey *et al.*, 2006). Canadian managed forests increased in biomass only  
31 slightly over 1990-2008, due to fires and beetle outbreaks (Stinson *et al.*, 2011). Several dozen sites across the moist  
32 tropics have been monitored to estimate forest biomass changes. In the Amazon (Malhi *et al.*, 2009a; Phillips *et al.*,  
33 2009) forest biomass has generally increased in recent decades, dropping after a drought in 2005. Globally, mature  
34 forests are withdrawing from the atmosphere one fourth of human CO<sub>2</sub> emissions while regrowth forests withdraw  
35 an additional 17%. This global terrestrial sink is offset by the losses of forest carbon to the atmosphere through  
36 tropical deforestation and land-use (Pan *et al.*, 2011).  
37

38 The carbon stock in global soils, including litter, peatlands and permafrost, is estimated to be in the order of 3300  
39 PgC (Davidson *et al.*, 2011), which is about ten times more than is contained in forest biomass (Kindermann *et al.*,  
40 2008). The size of this stock represents the balance of inputs from primary productivity and soil respiration. Soil  
41 respiration increases with increasing temperature, but the sensitivity remains uncertain (Davidson and Janssens,  
42 2006). An analysis of long-term soil respiration measurements from around the world suggests that soil respiration  
43 has increased over the past two decades by an amount of 0.1PgC/y, some of which may be due to increased  
44 productivity (Bond-Lamberty and Thomson, 2010). Flooded coastal soils also show increases in respiration, larger  
45 than increases in production (Kirwan and Blum, 2011).  
46

#### 47 4.3.2.4. Evapotranspiration and its Role in the Terrestrial Water Cycle

48 Transpiration is affected by multiple factors (Luo *et al.*, 2008) including temperature, humidity, soil moisture, solar  
49 radiation and CO<sub>2</sub> concentration. Total evapotranspiration (ET: transpiration through plant stomata plus evaporation  
50 from the ground surface and leaf surfaces) is monitored with flux towers, but since most records are at most 15 years  
51  
52  
53  
54

1 duration (FLUXNET, 2012) there is insufficient data to calculate large-scale, long-term trends. ET can also be  
2 estimated from meteorological observations using the Penman-Monteith equation (Monteith, 1965; Penman, 1948)  
3 or simulated with models constrained by observations. Estimates of ET from 1120 globally distributed stations  
4 indicate that global land mean ET increased by approximately 2.2% between 1982 and 2002, a rate of increase of  
5  $0.5 \text{ mm yr}^{-2}$  (Wang *et al.*, 2010b), while other studies using constrained models in combination with other methods  
6 indicated trends of between  $0.25 \text{ mm yr}^{-2}$  to  $1.1 \text{ mm yr}^{-2}$  during the 1980s and 1990s but with a plateau or even  
7 decline since approximately 2000, attributed to reduced net radiation (Vinukollu *et al.*, 2011; Zeng *et al.*, 2012). A  
8 multi-model study using a data-driven empirical model and process-based land models (Jung *et al.*, 2010) also  
9 suggests that global evapotranspiration rose from the 1980s to the late 1990s but this trend then ceased, with  
10 increasing soil moisture limitations being cited as the cause.

11  
12 Experimental studies demonstrate that increasing  $\text{CO}_2$  concentrations leads to a decrease in transpiration and  
13 increase in intrinsic water use efficiency (iWUE, the ratio of photosynthesis to stomatal conductance, Leakey *et al.*,  
14 2009), which may act to offset climate-driven ET increases or precipitation decreases to some extent (Luo *et al.*,  
15 2008). A two-year experimental study also showed that warming can also decrease grassland transpiration by  
16 leading to earlier spring senescence (Zavaleta *et al.*, 2003b). Historical changes in iWUE can be inferred from  
17 records of stable carbon isotopes in woody plants (Peñuelas *et al.*, 2011) and even the bodies of herbivores (Barbosa  
18 *et al.*, 2010) since iWUE has been shown to be related to the change in the carbon isotope discrimination  $\Delta^{13}\text{C}$   
19 (Duquesnay *et al.*, 1998). A meta-analysis of studies at 47 sites across 5 ecosystem types (Peñuelas *et al.*, 2011)  
20 suggests that iWUE for mature trees increased by 20.5% between the 1970s and 2000s. Increased iWUE since pre-  
21 industrial times (1850 or before) has also been found at several forest sites (Gagen *et al.*, 2011; Andreu-Hayles *et*  
22 *al.*, 2011; Loader *et al.*, 2011; Nock *et al.*, 2011) and also in a temperate semi-natural grassland since 1857 (Koehler  
23 *et al.*, 2010), although in one boreal tree species iWUE ceased to increase after 1970 (Gagen *et al.*, 2011).

#### 24 25 26 4.3.2.5. *Changes in Species Range, Abundance and Extinction*

27  
28 Species respond to climate change through genotypic and phenotypic adaptation, by moving out of unfavorable and  
29 into favorable climates, or by going locally or globally extinct (Dawson *et al.*, 2011, Bellard *et al.*, 2012; section  
30 4.2.2). These responses to climate change can potentially have large impacts on biodiversity and ecosystem services.  
31 Genotypic adaptation in the face of strong selection pressure from climate change is typically accompanied by large  
32 reductions in abundance (see section 4.4.1.2). Species range shifts are accompanied by changes in abundance, local  
33 extinctions and colonization that can alter ecosystem services when they affect dominant species such as trees,  
34 keystone species such as pollinators, or species that are vectors for disease. Global extinctions result in the  
35 permanent loss of unique combinations of genes.

36  
37 Substantial evidence has accumulated since the AR4 report reinforcing the conclusion that terrestrial plant and  
38 animal species' ranges have moved in response to warming over the last several decades and that this movement is  
39 projected to accelerate over the coming decades under high rates of climate change. Some changes in species  
40 abundances appear to be linked to climate change in a predictable manner with species abundances increasing in  
41 areas where climate has become more favorable and vice versa. In contrast, uncertainties concerning attribution of  
42 recent and projections of future global species extinctions due to climate change have become more apparent since  
43 the AR4 report.

44  
45 *Observed Species Range Shifts* - The number of studies looking at observed range shifts and the breadth of species  
46 examined has greatly increased since the AR4 report. The most important advances since AR4 concern  
47 improvements in understanding the relationship between range shifts and changes in climate over the last several  
48 decades. The "uphill and poleward" view of species range shifts in response to recent warming (Parmesan and Yohe,  
49 2003; Parmesan, 2006; Fischlin *et al.*, 2007; Chen *et al.*, 2011) is an useful simplification of species response to  
50 changing climate. However, responses to warming are conditioned by changes in precipitation, land use, species  
51 interactions and many other factors. Investigations of the mechanisms underlying observed range shifts show that  
52 climate signals can often be detected, but the impacts of and interactions between changing temperature,  
53 precipitation and land use often result in range shifts that are downhill or away from the poles (Rowe *et al.*, 2010;  
54 Crimmins *et al.*, 2011; Hockey *et al.*, 2011; McCain and Colwell, 2011; Rubidge *et al.*, 2011; Pauli *et al.*, 2012;

1 Tingley *et al.*, 2012; Zhu *et al.*, 2012). There are large differences in the ability of species groups and species within  
2 species groups to track changes in climate through range shifts (Angert *et al.*, 2011; Mattila *et al.*, 2011; Chen *et al.*,  
3 2011). For example, butterflies appear to be able track climate better than birds (community shifts - Devictor *et al.*,  
4 2012; but see Chen *et al.* (2011 for range shifts) while some plants appear to be lagging far behind climate except in  
5 mountainous areas (Bertrand *et al.*, 2011; Doxford and Freckleton, 2012; Gottfried *et al.*, 2012; Zhu *et al.*, 2012).  
6 There is also growing evidence that responses at the "trailing edge" of species distributions (i.e., local extinction in  
7 areas where climate has become unfavorable) are often less pronounced than responses at the "leading edge" (i.e.,  
8 colonization of areas where climate has become favorable), which may be related to differences in the rates of local  
9 extinction vs. colonization processes (Doak and Morris, 2010; Chen *et al.*, 2011; Brommer *et al.*, 2012; Sunday *et*  
10 *al.*, 2012) and difficulties in detecting local extinction (Thomas *et al.*, 2006).

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

27  
28 *Future Range Shifts* - Projections of future species range shifts since AR4 report have been dominated by studies  
29 using ecological niche models (ENMs) that estimate future ranges based on current relationships between climate  
30 and species distribution (also called "species distribution models", or "bioclimatic models" when models depend  
31 entirely on climate factors; Peterson *et al.*, 2011). A variety of process-based species distribution models are also  
32 being developed and more widely used (Kearney *et al.*, 2009; Dawson *et al.*, 2011; Cheaib *et al.*, 2012). Recent  
33 model comparisons suggest that in some instances bioclimatic models predict larger range shifts than process-based  
34 models (Morin and Thuiller, 2009; Kearney *et al.*, 2010; Cheaib *et al.*, 2012) although in other cases process-based  
35 models predict larger shifts (Buckley *et al.*, 2012). Projected future species shifts are broadly coherent with species  
36 responses to climate change in the paleontological record and with observed recent species shifts (see section 4.2.2  
37 and above). There has been some progress in model validation, such as the use of hindcasting of observed recent or  
38 paleontological range shifts, but validation still needs to be reinforced using a wide array of data types (Green *et al.*,  
39 2008; Pearman *et al.*, 2008; Nogues-Bravo *et al.*, 2010; Dawson *et al.*, 2011). A major limitation of these models is  
40 that the vast majority do not account for realistic species displacement rates (i.e., rates at which species are able to  
41 shift their ranges); as such, they only indicate changes in areas of favorable and unfavorable climate from which  
42 possible shifts in species distribution can be inferred.

43  
44 A small, but growing number of new analyses and models developed since the A4 report permit the estimation the  
45 ability of a large range of species to track climate change. These projections are based on i) past and future climate  
46 velocity, which is a measure of the rate of climate displacement across a landscape and provides an indication of the  
47 speed at which an organism would need to move in order to keep pace with the changing climatic conditions (Loarie  
48 *et al.*, 2009; Burrows *et al.*, 2011; Chen *et al.*, 2011; Sandel *et al.*, 2011; Schippers *et al.*, 2011; Feeley and Rehm,  
49 2012; Schloss *et al.*, 2012; Dobrowski *et al.*, 2013) and ii) species displacement rates across landscapes with and  
50 without habitat fragmentation for very broad range of species (e.g., Stevens *et al.*, 2010b; Nathan *et al.*, 2011;  
51 Barbet-Massin *et al.*, 2012; Kappes and Haase, 2012; Meier *et al.*, 2012; Schloss *et al.*, 2012; see additional  
52 references in Figure 4-6 legend). Figure 4-6 provides a simplified comparison of these rates as means of illustrating  
53 the projected abilities of species to track climate. This simplified analysis is coherent with more realistic projections  
54 of climate induced species displacement across landscapes, some of which include additional constraints such as

1 habitat fragmentation or competition (Barbet-Massin *et al.*, 2012; Meier *et al.*, 2012; Schloss *et al.*, 2012).  
2 Comparison of these rates indicates whether species are projected to be able to track climate as it changes, i.e., when  
3 species displacement capacity exceeds climate velocity. When displacement rates are lower than projected climate  
4 velocities this indicates that species may be unable to keep pace with climate change.  
5

6 Rates of climate change over the 20<sup>th</sup> and projected for the 21<sup>st</sup> century are shown in Figure 4-6A. Rates of climate  
7 change for global land surfaces are given for IPCC AR5 climate projections for a wide range of greenhouse gas  
8 emissions scenarios (i.e., IPCC RCP scenarios, Knutti and Sedlacek, 2012). Rates of global warming for land  
9 surfaces have averaged ca. 0.03 °C/yr since 1980. At the low end of projected future rates of warming, rates  
10 decrease over time reaching near zero by the end of the century (RCP 2.6). At the high end, projected rates increase  
11 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  
12 upper bound for this scenario. Background colors in Figure 4-6A indicate the degree to which species may be able  
13 or unable to track suitable climates based on corresponding climate velocities (Figure 4-6B) and rates of  
14 displacement for a broad range of species groups (Figure 4-6C). Blue background color indicates that nearly all  
15 species will be able to track climate change in all areas; orange indicates that some species will be unable to track  
16 climate especially in flat areas; and red indicates that many species groups will be unable to track climate except in  
17 mountainous regions.  
18

19 Climate velocity depends on regional rates of climate change and the degree of altitudinal relief (Figure 4-6B,  
20 Loarie *et al.*, 2009; Dobrowski *et al.*, 2013). For example, climate velocity is low in mountainous areas, because  
21 climatic gradients are strong, and in areas where climate change is low (Figure 4-6B, leftmost axis). Climate  
22 velocity is high (Figure 4-6B, rightmost axis) in flat areas (e.g., Amazon basin) or areas where projected climate  
23 change is high (e.g., Arctic regions). In flat areas, climate velocity may exceed 8 km/yr for the highest rates of  
24 projected climate change (SRES A2 or RCP 8.5).  
25

26 Rates of displacement vary greatly within and among species groups (Figure 4-6C). Some species groups, notably  
27 plants and especially trees, have very low displacement capacity. Other species groups such as butterflies, birds and  
28 large vertebrates generally have a very high capacity to disperse across landscapes. Small-ranged species across  
29 several groups (amphibians, mammals and birds) are markedly absent from areas with high climate velocities in the  
30 past, suggesting a low dispersal capacity (Sandel *et al.*, 2011). Current and future rates of climate change correspond  
31 to climate velocities that exceed rates of displacement for several species groups for most climate change scenarios.  
32 This is particularly true for mid- and late-successional trees that have maximum displacement rates that are on the  
33 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  
34 of mountainous areas, though there is uncertainty concerning the potential role of long-distance dispersal (Pearson,  
35 2006). Primates have substantially higher dispersal capacity than trees; however, a large fraction of primates are  
36 found in regions with very high climate velocities (e.g., the Amazon basin), thereby putting them at high risk of  
37 being unable to track climates even at relatively low rates of climate change. On a global average, many rodents, as  
38 well as some carnivores and freshwater mollusks are projected to be beyond their limits to track climate at high rates  
39 of climate change (i.e., >0.06°C/yr). These projected differences in species ability to keep pace with future climate  
40 change are broadly coherent with observations of species ability or inability to track recent global warming (see  
41 above).  
42

43 Humans can enhance species displacement by intentionally or unintentionally dispersing individuals or propagules  
44 (arrow on right of Figure 4-6C pointing upwards). For example, many economically important tree species may be  
45 deliberately moved on large scales as part of climate adaptation strategies in forestry in some regions (Lindner *et al.*,  
46 2010). Human activities can also substantially reduce displacement rates. For example, habitat fragmentation  
47 typically reduces displacement rates, sometimes substantially (Eycott *et al.*, 2012; Hodgson *et al.*, 2012; Meier *et al.*,  
48 2012; Schloss *et al.*, 2012; arrow on right pointing downwards). The degree to which habitat fragmentation slows  
49 displacement depends on many factors including the spatial pattern of fragmentation and corridors, maximum  
50 dispersal distances, population dynamics and the suitability of modified habitats as stepping-stones (Pearson and  
51 Dawson, 2003).  
52

53 Species that cannot move fast enough to keep pace with the rate of climate change will lose favorable climate space  
54 and potentially experience large range contractions, whereas displacement that keeps pace with climate change may

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

11  
12 Significant uncertainties arising from translating rates of warming into climate velocities and from estimating  
13 displacement rates mean that the ability to track future climate can only be projected with *low confidence* across all  
14 species examined. For trees there is *medium confidence* in these projections due to the large number of studies of  
15 past, current and future displacement rates (*robust evidence* and *medium agreement*). Climate velocities are  
16 calculated using a variety of methods and spatial resolutions making direct comparisons difficult, so climate  
17 velocities in Figure 4-6B are based on semi-quantitative comparisons of several studies (see Figure 4-6 legend) and  
18 have only *low confidence* (*limited evidence* and *medium agreement*). For the global average climate velocity (Figure  
19 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  
20  $\approx 0.03$  °C/yr for projected SRES A1B 21<sup>st</sup> century global land warming). Highest estimates are about four times the  
21 values on the axis (Burrows *et al.*, 2011; 2.7 km/yr  $\approx 0.02$  °C/yr global land warming from 1960-2009), but these  
22 high estimates may be artifacts of very large spatial resolutions used in this analysis (Dobrowski *et al.*, 2013). In  
23 addition, the rates used in this analysis are based on temperature alone and most analyses suggest that including  
24 more climate factors increases climate velocity (Feeley and Rehm, 2012; Dobrowski *et al.*, 2013). Species  
25 displacement rates are calculated based on a very wide range of methods including rates of displacement in the  
26 paleontological record, rates of current range shifts due to climate warming, models of dispersal and establishment,  
27 maximum observed dispersal distances and genetic analyses (e.g., Kinlan and Gaines, 2003; Stevens *et al.*, 2010b).  
28 There are often large differences in estimates of dispersal rates across methods (e.g., Kinlan and Gaines, 2003;  
29 Stevens *et al.*, 2010b) due to intrinsic uncertainties in the methods and differences in the mechanisms included. For  
30 example, estimates of tree displacement rates are frequently based on models or observations that explicitly or  
31 implicitly include both dispersal of seeds and biotic and abiotic factors controlling establishment of adult trees.  
32 Displacement rates of trees are often more strongly limited by establishment than dispersal (Higgins *et al.*, 2003;  
33 Meier *et al.*, 2012). It is reasonable to expect that limits on establishment could also be important for other species  
34 groups, but often only dispersal rates have been calculated (e.g., mammals, birds and phytophagous insects). As  
35 such, the displacement rates for these species may be optimistic. For some species groups such as trees, there are a  
36 wide range of published estimates of displacement rates leading to *high confidence* in the estimates in Figure 4-6C.  
37 Considerably less is known about displacement rates for other species groups in response to climate change (e.g.,  
38 some mammal groups, mollusks), so we have only *low to medium confidence* in estimates of their dispersal capacity.

39  
40 [INSERT FIGURE 4-6 HERE

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

1 Sandel *et al.*, 2011; Schippers *et al.*, 2011; Feeley and Rehm, 2012; Schloss *et al.*, 2012). The three axes represent  
2 estimated climate velocities are representative of mountainous areas (left), averaged across all global land area  
3 (center, usually geometric means), and regions that are flat or have high rates climate change (right). (C) Rates of  
4 displacement for terrestrial plants - predominantly based on dispersal and establishment - were derived from  
5 paleobotanical records, modern plant invasion rates and genetic analyses (Kinlan and Gaines, 2003). The box  
6 represents ~95% of the observations in Kinlan and Gaines (2003) and the bar represents a qualitative estimate of the  
7 median. Displacement estimates for trees are based on reconstructed rates of tree migration during the Holocene  
8 (Clark, 1998; Clark *et al.*, 2003; Kinlan and Gaines, 2003; McLachlan *et al.*, 2005; Nathan, 2006; Pearson, 2006)  
9 and modeled tree dispersal and establishment in response to future climate change (Higgins *et al.*, 2003; Iverson *et al.*,  
10 2004; Epstein *et al.*, 2007; Goetz *et al.*, 2011; Nathan *et al.*, 2011; Meier *et al.*, 2012; Sato and Ise, 2012). The  
11 box represents ~95% of the estimates and the bar is a qualitative estimate of the median. Displacement rates for  
12 mammals were based on modeled dispersal rates of wide range of mammal species from Schloss *et al.* (2012). The  
13 box represents 1.5 x the inter-quartile range of the estimates in Schloss *et al.* (2012) and the bar is the median.  
14 Several groups of mammals have not been plotted because they include a relatively small number of species.  
15 Estimates for birds are based on observed rates of displacement (Chen *et al.*, 2011; La Sorte and Jetz, 2010) and on  
16 modeled dispersal rates in response to projected climate change (Schippers *et al.*, 2011; Barbet-Massin *et al.*, 2012),  
17 but very low confidence in these estimates makes it difficult to set bounds or indicate central tendency.  
18 Displacement rates for phytophagous insects are based on observed dispersal rates (Kinlan and Gaines, 2003;  
19 Stevens *et al.*, 2010b; Sekar, 2012). The qualitative estimate of median dispersal rate exceeds the highest rates on  
20 the axis and is on the order of 100 km/yr. These dispersal rates do not take into account limitations imposed by host  
21 plants and habitats. Displacement estimates for freshwater mollusks correspond to the range of dispersal given for  
22 passive plus active dispersal mechanisms for upstream movement in Kappes and Haase (2012).]  
23

24 *Observed Changes in Abundance and Local Extinctions* - Observations of range shifts imply changes in abundance;  
25 i.e., colonization at the "leading edge" and local extinction at the "trailing edge" of ranges. Evidence that the  
26 attribution of these responses to recent changes in climate can be made with *high confidence* is reviewed above, in  
27 the AR4 report and by Cahill *et al.* (2013). Changes in abundance, as measured by changes in the population size of  
28 individual species or shifts in community structure, also have occurred within existing range limits in response to  
29 recent global warming (*high confidence*) (Thaxter *et al.*, 2010; Bertrand *et al.*, 2011; Naito and Cairns, 2011;  
30 Rubidge *et al.*, 2011; Devictor *et al.*, 2012; Tingley *et al.*, 2012; Cahill *et al.*, 2013; Ruiz-Labourdette *et al.*, 2013).  
31 More confident attribution to recent global warming is hindered by confounding factors such as disease, land use  
32 change and invasive species (Cahill *et al.*, 2013). A new tentative conclusion since the AR4 is that climate related  
33 local extinctions appear to be more strongly related to species interactions than to physiological tolerance limits (*low*  
34 *confidence*) (Cahill *et al.*, 2013). This gives weight to concerns that biological interactions, which are poorly  
35 understood and modeled, may play a critical role in mediating the impacts of future climate change on species  
36 abundance and local extinctions (Dunn *et al.*, 2009; Bellard *et al.*, 2012; Urban *et al.*, 2012; Hannah, 2012).  
37

38 A few examples illustrate the types of changes in abundance and local extinctions that are being observed and the  
39 challenges in attributing these to recent global warming. Some of the clearest examples of climate-related changes in  
40 species populations come from high latitude ecosystems where non-climate drivers are of lesser importance. For  
41 example, both satellite data and a large number of long-term observations indicate that shrub abundance is generally  
42 increasing over broad areas of Arctic tundra, which is coherent with predicted shifts in community structure due to  
43 warming (Epstein *et al.*, 2007; Goetz *et al.*, 2011; Myers-Smith *et al.*, 2011). In the Antarctic, two native vascular  
44 plants, Antarctic pearlwort (*Colobanthus quitensis*) and Antarctic hair grass (*Deschampsia antarctica*) have become  
45 more prolific over recent decades, perhaps because they benefit more from warming of soils than do mosses (Hill *et al.*,  
46 2011). Penguin populations have declined in several areas of the Antarctic, including a recent local extinction of  
47 an Emperor penguin population that has been attributed to regional changes in climate (Trathan *et al.*, 2011). The  
48 attribution to regional climate change is well supported, but the link to global warming is tenuous (Barbraud *et al.*,  
49 2011).  
50

51 Mountains also provide good examples of climate signals in abundance and local extinction because of very strong  
52 climate gradients. The AR4 report already highlighted these responses and the case for changes in abundance, in  
53 particular plants, has become stronger since then. For example, Pauli *et al.* (2012) reported an increase in species  
54 richness from plant communities of mountain tops in the European boreal and temperate zones due to increasing

1 temperatures and a decrease in species richness on the Mediterranean mountain tops, probably due to a decrease in  
2 the water availability in Southern Europe. An increase in the population size of warm adapted species at high  
3 altitudes also appears to be attributable to increasing temperatures (Gottfried *et al.*, 2012). However, these  
4 attributions are complicated by other anthropogenic influences such as changes in grazing pressure, atmospheric  
5 nitrogen deposition, and forest management practices (Gottfried *et al.*, 2012). Altitudinal gradients in local and  
6 global extinctions of amphibians also contributed to the attribution of these extinctions to recent global warming,  
7 although this attribution remains controversial (see below).

8  
9 *Projected Changes in Abundance and Local Extinction* - Ecological niche models do not predict population changes,  
10 but the shifts in suitable climates can be used to infer areas where species populations might decline or increase.  
11 Projected areas of local extinction from these types of models ranging from near 0% of the current range to more  
12 than 95% (Settele *et al.*, 2008; Bellard *et al.*, 2012), and projected local colonization rates are equally variable.  
13 There has been progress in coupling species distribution and species abundance models for a wide range of  
14 organisms (Keith *et al.*, 2008; Midgley *et al.*, 2010; Matthews *et al.*, 2011; Schippers *et al.*, 2011; Oliver *et al.*,  
15 2012; Renwick *et al.*, 2012). These approaches have the substantial advantage of predicting extinction risk directly,  
16 rather than by inference from changes in climate suitability (Fordham *et al.*, 2012). The main conclusion from these  
17 studies is species response to climate change is determined by a combination of factors, including its environmental  
18 niche, demographics and life history traits, as well as interactions among these factors (Aiello-Lammens *et al.*, 2011;  
19 Conlisk *et al.*, 2012; Fordham *et al.*, 2012; Swab *et al.*, 2012).

20  
21 Changes in abundances will also be accompanied by changes in genetic diversity. At an intraspecific level, future  
22 climate change projections are projected to induce severe losses of genetic diversity (Balint *et al.*, 2011). In addition,  
23 there is theoretical and observational evidence that range contractions will reduce genetic diversity (Pauls *et al.*,  
24 2013), but that the loss of genetic diversity will depend on rates of migration and range contraction (Arenas *et al.*,  
25 2012). Reductions in genetic diversity may then decrease the ability of species to adapt to further climate change or  
26 other global changes. Although future projections of climate change impacts do not appear to result in the loss of  
27 more phylogenetic diversity than expected by chance, projected species losses are projected to lead to phylogenetic  
28 homogenization across European plant, bird and mammal communities (Thuiller *et al.*, 2011, but see Davies *et al.*,  
29 2011). Climate change may also compound losses of genetic diversity that already occurring due other global  
30 changes such as the introduction of alien species or habitat fragmentation (Winter *et al.*, 2009; section 4.2.4.6).

31  
32 *Observed Global Extinctions* - Global species extinctions, many of them caused by human activities, are now close  
33 to the upper limits of observed natural rates of extinction in the fossil record (Barnosky *et al.*, 2011). Most  
34 extinctions over the last several centuries can be attributed to habitat loss, overexploitation or invasive species  
35 (Millennium Ecosystem Assessment, 2005a; Hofmann and Todgham, 2010; Cahill *et al.*, 2013). Of the more than  
36 800 global extinctions documented by the IUCN, only 20 have been tenuously linked to recent climate change  
37 (Cahill *et al.*, 2013). Mollusks, especially freshwater mollusks, have by far the highest rate of documented  
38 extinctions of all species groups (Barnosky *et al.*, 2011). Mollusk extinctions are primarily attributed to invasive  
39 species, habitat modification and pollution — changes in climate are rarely evoked as a driver (Lydeard *et al.*, 2004;  
40 Regnier *et al.*, 2009; Chiba and Roy, 2011; but see a few cases in Kappes and Haase, 2012; Cahill *et al.*, 2013).  
41 Freshwater fish have the highest documented extinction rates of all vertebrates, and again very few have even been  
42 tenuously attributed to changing climate (Burkhead, 2012; Cahill *et al.*, 2013). In contrast, changes in climate have  
43 been identified as one of the key drivers of extinctions of amphibians (Pounds *et al.*, 2006). There have been more  
44 than 160 probable extinctions of amphibians documented over the last two decades, many of them in Central  
45 America (Pounds *et al.*, 2006; Kiesecker, 2011). The most notable cases have been the golden toad and Monteverde  
46 harlequin frog (*Atelopus varius*) of Central America, which belong to a group of amphibians with high rates of  
47 extinction ascribed to global warming with "very high confidence" (Pounds *et al.*, 2006; Fischlin *et al.*, 2007). This  
48 case has raised a number of important issues about attribution since i) the proximate causes of extinction of these  
49 and other Central American frogs appear to be an extremely virulent invasive fungal infection and land use change,  
50 with regional changes in climate as a potential contributing factor and ii) changes in regional climate may have been  
51 related to natural climate fluctuations rather than anthropogenic climate change (Sodhi *et al.*, 2008; Lips *et al.*, 2008;  
52 Collins, 2010; Anchukaitis and Evans, 2010; Vredenburg *et al.*, 2010; Kiesecker, 2011; McKenzie and Peterson,  
53 2012; McMenamin and Hannah, 2012). While this case highlights difficulties in attribution of extinctions to recent  
54 global warming, it also points to a growing consensus that it is the interaction of climate change with other global



1 change pressures that poses the greatest threat to species (Pereira *et al.*, 2010; Hof *et al.*, 2011; Brook *et al.*, 2008).  
2 Overall, there is *very low confidence* that observed species extinctions can be attributed to recent climate warming  
3 due to the very low fraction of species for which global extinction has been ascribed to climate change and tenuous  
4 nature of most attributions.

5  
6 *Projected Future Species Extinctions* - Projections of future extinctions due to climate change have received  
7 considerable attention since the AR4 report. The AR4 report stated with *medium confidence* "that approximately 20-  
8 30% of the plant and animal species assessed to date are at increasing risk of extinction as global mean temperatures  
9 exceed a warming of 2-3°C above pre-industrial levels" (Fischlin *et al.*, 2007). All model-based analyses since the  
10 AR4 broadly confirm this concern, leading to *very high confidence* that climate change will contribute to increased  
11 extinction risk for terrestrial species over the coming century (Pereira *et al.*, 2010; Sinervo *et al.*, 2010; Pearson,  
12 2011; Warren *et al.*, 2011; Hannah, 2012; Ihlow *et al.*, 2012; Bellard *et al.*, 2012; Sekercioglu *et al.*, 2012; Wearn  
13 *et al.*, 2012). More generally, there is broad agreement that climate change will result in shifts in species' ranges and  
14 abundances, and that in the context of habitat fragmentation and other global change pressures this will contribute  
15 substantially to increased extinction risk of terrestrial species over the coming century (Pereira *et al.*, 2010).

16  
17 However, work since the AR4 also calls into question the ability of models to accurately quantify future extinction  
18 risk. Modeling studies have used a wide range of methods to estimate future extinction risk, generally inferring  
19 extinction risk indirectly from changes in availability of habitat and rarely taking into account demographic factors  
20 such as dispersal ability and generation time (Akçakaya *et al.*, 2006). All studies project increased extinction risk by  
21 the end of the 21st century due to climate change, but these estimates range from below 1% to above 50% of species  
22 in the groups that have been studied (Pereira *et al.*, 2010; Bellard *et al.*, 2012; Cameron, 2012). However, most  
23 models do not incorporate key processes that link climate change to population change. For example, models rarely  
24 account for genetic and phenotypic adaptive capacity, dispersal, the effects of habitat fragmentation and loss, and  
25 community interactions as well as, in plants, the effects of rising CO<sub>2</sub> concentrations. A general paucity of  
26 approaches to model validation, the large variation in the climate sensitivity of species groups and uncertainties  
27 about timescales involved in range reduction to extinction all lead to *very low confidence* that models currently  
28 predict extinction risk accurately (Kuussaari *et al.*, 2009; Pereira *et al.*, 2010; Dawson *et al.*, 2011; Pearson, 2011;  
29 McMahon *et al.*, 2011; Araujo and Peterson, 2012; Bellard *et al.*, 2012; Fordham *et al.*, 2012; Kramer *et al.*, 2012;  
30 Hannah, 2012; Zurell *et al.*, 2012; Halley *et al.*, 2013). In addition, evidence from the paleontological record  
31 indicating very low extinction rates over the last several hundred thousand years of substantial natural fluctuations in  
32 climate - with a few notable exceptions such as large land animal extinctions during the Holocene - has also led to  
33 concern that forecasts of very high extinction rates due entirely to climate change may be overestimated (Botkin  
34 *et al.*, 2007; Willis and Bhagwat, 2009; Pereira *et al.*, 2010; Dawson *et al.*, 2011; Hof *et al.*, 2011; Willis and  
35 MacDonald, 2011; Wake, 2012). On the other hand, processes not accounted for in most models, such changes in  
36 biotic interactions such as pollination or predator-prey networks or non-linear changes in ecosystems with  
37 widespread consequences for resident species, mean that future extinction risks may also have been substantially  
38 underestimated, at least for certain areas and species groups (Schweiger *et al.*, 2008; Bellard *et al.*, 2012; Urban  
39 *et al.*, 2008; Nakazawa and Doi, 2012; Hannah, 2012) or overestimated (Menéndez *et al.*, 2008; Pateman *et al.*, 2012).  
40 Finally, there is growing awareness that most modeling analyses have not accounted for climatic variation at fine  
41 spatial scales (microclimate) that may increase (Randin *et al.*, 2009; Gillingham *et al.*, 2012; Suggitt *et al.*, 2012;  
42 Dobrowski *et al.*, 2013; Franklin *et al.*, 2013) or decrease (Trivedi *et al.*, 2008; Engler *et al.*, 2011) the likelihood of  
43 persistence of small populations under future climate change.

#### 46 **4.3.3 Impacts on Major Systems**

47  
48 This section covers impacts of climate change on broad types of terrestrial and freshwater ecosystems of the world.  
49 We have placed a particular emphasis on those areas of high vulnerability due to high exposure to climate change or  
50 that may be pushed past thresholds or "tipping points" by climate change.

51  
52 Figure 4-7 provides an overview of two perspectives on estimating ecosystem vulnerability to climate change at the  
53 global scale. Figures 4-7A and 4-7B show projected future climate change in relationship to current inter-annual  
54 variability (Diffenbaugh and Giorgi, 2012; see similar analyses by Beaumont *et al.*, 2011; Williams *et al.*, 2007b).

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

27  
28 [INSERT FIGURE 4-7 HERE

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

38  
39 An issue that emerged in the AR4 report and has grown substantially in prominence since then is that of thresholds  
40 or ‘tipping points’ (Lenton *et al.*, 2008; Scheffer *et al.*, 2009; Leadley *et al.*, 2010). Tipping points occur when  
41 positive feedback processes dominate over negative feedback loops, and the system begins to change as a result of  
42 both its internal dynamics and the external forcings, leading to a change in state that is difficult or slow to reverse  
43 (Lenton *et al.*, 2008; Scheffer *et al.*, 2009; Leadley *et al.*, 2010). In the AR5, tipping points are considered “a level  
44 of change in system properties beyond which a system reorganizes, often abruptly, and persists in its new state even  
45 if the drivers of the change are abated” (Glossary). Many examples of such thresholds have now been identified  
46 (Scheffer, 2009). Most are at the local scale, but the potential existence of ecological thresholds at a sufficient scale  
47 to have regional or global consequences is high. Posited examples include a drought and temperature threshold in  
48 the Amazon beyond which forest dieback and fires could contribute to large C fluxes to the atmosphere, or thawing  
49 of Arctic permafrost leading to emissions of CH<sub>4</sub> and CO<sub>2</sub> in sufficient quantities to further warm the Earth and  
50 amplify the permafrost warming (Lenton *et al.*, 2008; Leadley *et al.*, 2010). Ecosystem water balance thresholds that  
51 are surpassed through changes in temperature and precipitation, both gradual and through extreme events, may be a  
52 widespread phenomenon across a range of biomes (Knapp *et al.*, 2008a). Large-scale tipping points have not  
53 occurred in the recent past, but there is good evidence for tipping points in the distant past (section 4.2.2) and the  
54 sub-sections below highlight reasons for concern that they could occur in the near future. A thorough analysis of all

1 the highlighted tipping points is not possible in this section, so we have highlighted some of the most important and  
2 well-studied tipping points. Others are discussed in Lenton *et al.* (2008) and Leadley *et al.* (2010).

#### 3 4 5 4.3.3.1. Forests and Woodlands

6  
7 Forests and woodlands, are the principal providers of timber and pulp, biofuel and an important and steady source of  
8 good-quality water worldwide. They also supply other services, including food and, cultural services such as  
9 recreation. Forests are the habitat of a large fraction of the earth's terrestrial biodiversity, especially in tropical  
10 regions (Gibson *et al.*, 2011). Climate change and forests interact strongly. Climate and atmospheric CO<sub>2</sub>  
11 concentrations are major drivers of forest productivity and forest dynamics. At the same time forests play an  
12 important role in controlling climate through the large amounts of carbon they can store or release, and through  
13 direct effects on the climate such as the absorption or reflection of solar radiation (albedo), cooling through  
14 evapotranspiration and the production of cloud-forming aerosols (Arneth *et al.*, 2010; Pan *et al.*, 2011; Pielke *et al.*,  
15 2011).

16  
17 Combinations of ground based observations, atmospheric carbon budgets and satellite measurements indicate that  
18 forests are currently a net sink for carbon at the global scale. It is estimated that intact and regrowing forests  
19 currently contain  $861 \pm 66$  PgC and stored  $4.0 \pm 0.7$  Pg C year<sup>-1</sup> globally between 2000 and 2007 (Pan *et al.*, 2011;  
20 WG1 Chapter 6; Canadell *et al.*, 2007; Le Quere *et al.*, 2009). The carbon stored in intact and regrowing forests was  
21 counterbalanced by a release due to land-use change of  $2.8 \pm 0.4$  Pg C year<sup>-1</sup> over this same period due to tropical  
22 deforestation, resulting in a net C balance for global forests of  $1.2 \pm 0.8$  Pg C year<sup>-1</sup>.

23  
24 The phrase 'biophysical effects' is shorthand for the effect forests have on the climate other than through being  
25 sources and sinks of greenhouse gases. These effects are now well documented, significant and are increasingly  
26 included in models of global and regional climate change. Observations and models indicate that boreal and tropical  
27 forests have the largest influence on climate, but for different reasons: boreal forests have low albedo (i.e., reflect  
28 less solar radiation); and tropical forests pump more water and aerosols into the atmosphere than non-forest systems  
29 in similar climates (Davin and de Noblet-Ducoudre, 2010; Delire *et al.*, 2011; Pielke *et al.*, 2011). Overall, this  
30 means that the biophysical effect of boreal forests is to warm the atmosphere and tropical forests to cool the  
31 atmosphere, compared to non-forest systems (Davin and de Noblet-Ducoudre, 2010). It has also been shown that  
32 forests influence regional precipitation through biophysical effects: deforestation in the tropics can alter regional  
33 precipitation (Butt *et al.*, 2011) and there is growing evidence of similar effects in temperate forests (Pielke *et al.*,  
34 2011).

35  
36 The future of the interaction between climate and forests is unclear. The carbon stored by intact and regrowing  
37 forests appears have stabilized compared to the 1990's, after having increased in the 1970's and 1980's (Canadell  
38 *et al.*, 2007; Pan *et al.*, 2011). The drivers behind the forest carbon sink vary greatly across regions. They include  
39 forest regrowth and simulation of C sequestration by climate change, rising atmospheric CO<sub>2</sub> concentrations and N  
40 deposition (Pan *et al.*, 2011). Most models suggest that rising temperatures, drought and fires will lead to forests  
41 becoming a weaker sink or a net carbon source before the end of the century (Sitch *et al.*, 2008; Bowman *et al.*,  
42 2009). Fires play a dominant role in driving forest dynamics in many parts of the world and the susceptibility to fire  
43 is projected to increase little for the lowest emissions scenario (RCP 2.6), but substantially for the high emissions  
44 scenario (RCP 8.5, Figure 4-8). Climate change-mediated disease and insect outbreaks could precipitate this  
45 transition (Kurz *et al.*, 2008). The greatest risks for large feedbacks from forests to climate arise from widespread  
46 tree mortality and fire in tropical forests and low latitude areas of boreal forests, as well as northward expansion of  
47 boreal forests into arctic tundra (Lenton *et al.*, 2008; Krieglner *et al.*, 2009; Good *et al.*, 2011).

48  
49 [INSERT FIGURE 4-8 HERE

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

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

3  
4 Recent evidence suggests that the stimulatory effects of global warming and rising CO<sub>2</sub> concentrations on tree  
5 growth may have already peaked in many regions (Charru *et al.*, 2010; Silva *et al.*, 2010; Silva and Anand, 2013)  
6 and that warming and changes in precipitation are increasing tree mortality in a wide range of forest systems, acting  
7 via heat stress, drought stress, pest outbreaks and a wide range of other indirect impact mechanisms (Allen *et al.*,  
8 2010a; Box 4-2). Detection of a coherent global signal is hindered by the lack of long-term observations in many  
9 regions, and attribution to climate change is difficult due to the multiplicity of mechanisms mediating mortality  
10 (Allen *et al.*, 2010a).

11  
12 Deforestation has slowed over the last decade (Meyfroidt and Lambin, 2011). This includes substantial reductions in  
13 tropical deforestation in some regions, such as the Brazilian Amazon, where deforestation rates declined rapidly  
14 after peaking in 2005 (Secretariat of the Convention on Biological Diversity, 2010). It is unclear if the global trend  
15 to reduced forest loss will continue - there are substantial pressures to deforest for the production of food and  
16 biofuels (Wise *et al.*, 2009; Meyfroidt and Lambin, 2011). However, there are a number of signs that tropical  
17 deforestation could slow substantially over the next few decades, although this is thought to require continued and  
18 substantial technological, institutional and policy innovations (Wise *et al.*, 2009; Meyfroidt and Lambin, 2011;  
19 Westley *et al.*, 2011).

20  
21 \_\_\_\_\_ START BOX 4-2 HERE \_\_\_\_\_

#### 22 23 **Box 4-2. Tree Mortality and Climate Change**

24  
25 Extensive tree mortality and widespread forest die-off linked to drought and temperature stress have been  
26 documented recently on all vegetated continents (Allen *et al.*, 2010a; Figure 4-9). Plot level datasets with  
27 appropriate spatial and temporal spans to detect long-term tree mortality trends (>20 years) are currently lacking for  
28 many regions (Anderegg *et al.*, 2013a), leading to *low confidence* in the ability to detect a global trend.  
29 Nevertheless, long-term increasing tree mortality rates associated with temperature increases and drought have been  
30 documented in boreal and temperate forests in western North America (van Mantgem *et al.*, 2009; Peng *et al.*,  
31 2011). Increased levels of tree mortality following drought episodes have also been detected across widespread plot  
32 networks in multiple tropical forests (Kraft *et al.*, 2010; Phillips *et al.*, 2010) and Europe (Carnicer *et al.*, 2011).  
33 Episodes of widespread die-off (high mortality rates of dominant tree species at a landscape scale) have been  
34 observed in multiple vegetation types, particularly in western North America, Australia, and southern Europe (Raffa  
35 *et al.*, 2008; Carnicer *et al.*, 2011; Anderegg *et al.*, 2013b). Some widespread die-off events have occurred  
36 concomitant with infestation outbreaks (Raffa *et al.*, 2008), where pest populations are also directly influenced by  
37 climate, such as population release by warmer winter temperatures (Bentz *et al.*, 2010). While strong attribution of  
38 extensive tree mortality to recent warming has been made in a few studies, the paucity of long-term studies of the  
39 mechanisms driving mortality means that there is *low confidence* that this attribution can be made at the global scale.

40  
41 Widespread die-off has influenced the species composition, structure and age demographics, and successional  
42 trajectories in these forests, and in some cases led to decreased plant species diversity and increased risk of invasion  
43 (Kane *et al.*, 2011; Anderegg *et al.*, 2012). Widespread mortality also has multiple effects on biosphere-atmosphere  
44 interactions and could play an important role in future carbon-cycle feedbacks through complex effects on forest  
45 biophysical properties and biogeochemical cycles (Breshears *et al.*, 2005; Kurz *et al.*, 2008; Anderson *et al.*, 2011).

46  
47 Projections of tree mortality due to climate stress and potential thresholds of widespread forest loss are currently  
48 highly uncertain (McDowell *et al.*, 2011). Most current global scale vegetation models have little-to-no mechanistic  
49 representation of tree mortality (Fisher *et al.*, 2010; McDowell *et al.*, 2011). Nonetheless, a global analysis of tree  
50 hydraulic safety margins found that more than 70% of surveyed tree species operate close to their limits of water  
51 stress tolerance (Choat *et al.*, 2012), indicating that vulnerability to drought and temperature stress will not be  
52 limited to arid and semi-arid forests. Furthermore, timescales of tree and plant community recovery following  
53 drought are largely unknown, but preliminary evidence from several systems indicates recovery times may be  
54 shorter than recent drought return intervals, leading to “compounding” effects of multiple droughts (Mueller *et al.*,

1 2005; Anderegg *et al.*, 2013b; Saatchi *et al.*, 2013). Projected increases in temperature are also expected to facilitate  
2 expansion of insect outbreaks poleward and up in altitude, which may also cause or contribute to widespread tree  
3 mortality (Bentz *et al.*, 2010).

4  
5 [INSERT FIGURE 4-9 HERE

6 Figure 4-9: Locations of observed drought- and heat-induced tree mortality around the Earth since 1970,  
7 documented by peer-reviewed studies. Global forest cover (dark green) and other wooded regions (light green)  
8 (FAO, 2005). Studies compiled through 2009 (red dots) are summarized and listed in Allen *et al.* (2010). Localities  
9 and measurement networks not included in Allen *et al.* (2010a), which are largely post-2009 studies, have been  
10 added to this map (white dots are specific locations and regional measurement networks are indicated by ovals).  
11 New locality references by region: Africa – Mehl *et al.* (2010); Gonzalez *et al.* (2012); van der Linde *et al.* (2011);  
12 Asia – Dulamsuren *et al.* (2009); Kharuk *et al.* (2013); Liu *et al.* (in revision); Zhou *et al.* (2013); Australasia –  
13 Brouwers *et al.* (2012, 2013); Fensham *et al.* (2012); Matusick *et al.*, 2012, 2013); Europe – Innes (1992); Peterken  
14 and Mountford (1996); Linares *et al.* (2009); Galiano *et al.* (2010); Vennetier and Ripert (2010); Aakala *et al.*  
15 (2011); Carnicer *et al.* (2011); Sarris *et al.* (2011); Marini *et al.* (2012); Vilà-Cabrera *et al.* (2012); Cailleret *et al.*  
16 (2013); North America – Fahey (1998); Barbour *et al.* (2007); Klos *et al.* (2009); Ganey and Vojta (2011); Peng *et*  
17 *al.* (2011); DeRose and Long (2012); Fellows and Goulden (2012); Kaiser *et al.* (2012); Kukowski *et al.* (2012);  
18 Millar *et al.*, 2012); Williams *et al.* (2012); Worrall *et al.* (2013); Garrity *et al.* (in review); South America – Enquist  
19 and Enquist (2011); Lewis *et al.* (2011); Saatchi *et al.* (2013).]

20  
21 \_\_\_\_\_ END BOX 4-2 HERE \_\_\_\_\_  
22  
23

#### 24 4.3.3.1.1. Impacts of climate change on boreal forests

25  
26 Most projections suggest a poleward expansion of forests into tundra regions, accompanied by a general shift in  
27 composition towards more temperate plant functional types (e.g., evergreen needleleaf being replaced by deciduous  
28 broadleaf; or in colder regions, deciduous needleleaf replaced by evergreen needleleaf; Lloyd *et al.*, 2011; Pearson *et*  
29 *al.*, 2013). At the same time, projections of climate-driven changes in boreal forests over the next few centuries  
30 remain divergent on some issues, partly as a result of different processes of change being considered in different  
31 models. In particular, the inclusion or exclusion of fire and insects makes a big difference, possibly making the  
32 boreal forest more susceptible to a rapid, non-linear or abrupt decline in some regions of the circum-Northern  
33 Hemisphere (Bernhardt *et al.*, 2011; Mann *et al.*, 2012; Scheffer *et al.*, 2012). Recent change (Box 4-2) and dynamic  
34 vegetation modeling (e.g., Sitch *et al.*, 2008) provide *high confidence* that regions of the boreal forest could witness  
35 widespread forest dieback. These shifts put at risk the boreal carbon sink, estimated at 0.5 Pg year<sup>-1</sup> in 2000-2007  
36 (Pan *et al.*, 2011; Mann *et al.*, 2012).

37  
38 Whereas boreal forest productivity is widely expected, with *medium confidence*, to increase as a result of warming  
39 (Hari and Kulmata, 2008; Bronson *et al.*, 2009; Zhao and Running, 2010; Van Herk *et al.*, 2011), and early analyses  
40 of satellite observations confirmed this trend in the 1980s, more recent and longer-term assessments indicate with  
41 *high confidence* that many areas of boreal forest have instead experienced productivity declines (Goetz *et al.*, 2007;  
42 Parent and Verbyla, 2010; Beck *et al.*, 2011b; de Jong *et al.*, 2011). The reasons for these “browning” trends have  
43 been debated but they are not directly related to fire disturbance (because fires produce random rather than  
44 systematic trends in time series). The best evidence to date indicates that warming-induced drought, specifically the  
45 greater drying power of air (vapor pressure deficit), induces photosynthetic down-regulation of boreal tree species,  
46 particularly conifer species, most of which are not adapted to the warmer conditions (Welp *et al.*, 2007; Bonan,  
47 2008; Van Herk *et al.*, 2011). Satellite evidence for warming-induced productivity declines has been corroborated  
48 by tree ring studies (Barber *et al.*, 2000; Hogg *et al.*, 2008; Beck *et al.*, 2011b; Porter and Pizaric, 2011; Griesbauer  
49 and Green, 2012) and long-term tree demography plots in more continental and densely forested areas (Peng *et al.*,  
50 2011; Ma *et al.*, 2012). Conversely, productivity has increased at the boreal-tundra ecotone where more mesic  
51 conditions support an expected warming-induced growth response (Rupp *et al.*, 2001; McGuire *et al.*, 2007;  
52 Goldblum and Rigg, 2010; Beck *et al.*, 2011b).

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

16  
17 There is *high confidence* that the vulnerability of the boreal biome to this cascading series of interacting processes  
18 (Wolken *et al.*, 2011), and their ultimate influence on climate feedbacks, differs between North America and  
19 northern Eurasia. The latter is dominated by deciduous conifer (larch) forest, extending from western Russia across  
20 central to eastern Siberia – a region more than twice the size of the North American boreal biome, most of it  
21 underlain by permafrost conditions of the Siberian environment. In terms of post-fire succession analogous to the  
22 North American boreal biome, larch function more like deciduous species than evergreen conifers, with greater  
23 density and biomass gain in more severely burned areas, given adequate seed survival through fire events or post-  
24 fire seed dispersal (Zyryanova, 2007; Osawa *et al.*, 2010; Alexander *et al.*, 2012). Although the fire regime has  
25 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.*,  
26 2012; Marlon *et al.*, 2013), the likelihood of regime shifts in larch forests is currently unknown, partly because  
27 larch are self-replacing (albeit at different densities) and partly because it is largely dependent on the fate of  
28 permafrost across the region.

29  
30 The vulnerability of permafrost to thawing and degradation with climate warming is critical not only for determining  
31 the rate of a boreal-tundra biome shift, and its associated net feedback to climate, but also for predicting the degree  
32 to which the mobilization of very large carbon stores frozen for centuries will exacerbate additional warming  
33 (Schuur *et al.*, 2008; 2009; Tarnocai *et al.*, 2009; Romanovsky *et al.*, 2010; Schaefer *et al.*, 2011; see also Section  
34 4.3.3.4). The extent and rate of permafrost degradation varies with temperature gradients from warmer  
35 discontinuous permafrost areas to colder, more continuous areas, but also with the properties of the soil composition  
36 and biology (e.g., Mackelprang *et al.*, 2011). The degree of thermokarsting associated with different substrates, and  
37 associated topographic relief, is tremendously variable because boreal vegetation in latter successional stages  
38 (evergreen conifers in North America) insulate permafrost from air temperature increases; soils with differing silt  
39 and gravel content tend to have different ice content that, when melted, produces different degradation and  
40 deformation rates; and other factors such as fire disturbance interactions with both vegetation cover and soil organic  
41 depth as insulating layers (Jorgenson *et al.*, 2010; Grosse *et al.*, 2011). This variability, and vulnerability, is poorly  
42 represented in earth system models (McGuire *et al.*, 2012) and is thus the emphasis of research initiatives currently  
43 underway. Carbon management strategies to keep permafrost intact, for example by removing forest cover to expose  
44 the land surface to winter temperatures (Zimov *et al.*, 2009) are impractical not only because of the vast spatial  
45 domain underlain by permafrost, but also because of the broad societal and ecological impacts that would result.

#### 46 47 48 4.3.3.1.2. *Impacts of climate change on temperate forests*

49  
50 The largest areas of temperate forest are found in eastern North America, Europe and eastern Asia. The overall trend  
51 for forests in these regions has until recently been an increase in growth rates of trees and in total carbon stocks.  
52 This has been attributed to a combination of increasing growing season length, rising atmospheric CO<sub>2</sub>  
53 concentrations, nitrogen deposition and forest management – specifically regrowth following formerly more  
54 intensive harvesting regimes (Ciais *et al.*, 2008). The relative contribution of these factors has been the subject of

1 substantial and unresolved debate (Boisvenue and Running, 2006). Most temperate forests are managed such that  
2 any change is and will be to a large extent anthropogenic. With the exception of Europe (Ciais *et al.*, 2008), the  
3 relative contribution of anthropogenic and environmental factors to forest growth and carbon uptake rates remains to  
4 be quantified.

5  
6 The world's temperate forests act as an important carbon sink (*high confidence* due to *robust evidence; high*  
7 *agreement*), absorbing  $0.7\pm 0.08$  Pg C year<sup>-1</sup> from 1990 to 1999 and  $0.8\pm 0.09$  from 2000 to 2007 (Pan *et al.*,  
8 2011). This represents 34% of global carbon accumulation in intact forests and 65% of the global net forest carbon  
9 sink (total sink minus total emissions from land use).

10  
11 Recent indications are that temperate forests and trees are beginning to show signs of climate stress, including: a  
12 reversal of tree growth enhancement in some regions (N America - Silva *et al.*, 2010; Silva and Anand, 2013;  
13 Europe - Charru *et al.*, 2010; Bontemps *et al.*, 2011; Kint *et al.*, 2012); increasing tree mortality (Allen *et al.*, 2010a,  
14 Box 4-2); and changes in fire regimes, insect outbreaks and pathogen attacks (Adams *et al.*, 2012; Edburg *et al.*,  
15 2012). In north-eastern France, widespread recent declines in growth rates of European beech (*Fagus sylvatica* L.)  
16 have been attributed to decreasing water availability (Charru *et al.*, 2010). These trends threaten the substantial role  
17 of temperate forests as net carbon sinks, but it is still unclear to what extent the observations are representative for  
18 temperate forests as a whole. Several studies find that tree growth rates in temperate forests passed their peak in the  
19 late 20<sup>th</sup> century and that the decline in tree growth rates can be attributed to climatic factors, especially drought or  
20 heatwaves (Charru *et al.*, 2010; Silva *et al.*, 2010). Extreme climate events have had a major impact on temperate  
21 forests over the last decade (Witte *et al.*, 2011; Kasson and Livingston, 2012; Ciais *et al.*, 2005). Extensive forest  
22 fires occurred in Russia during the exceptionally hot and dry summer of 2010 (Witte *et al.*, 2011). The complex  
23 interactions between climate and forest management in determining susceptibility to extreme events make it difficult  
24 to unequivocally attribute these events to recent climate warming (Allen *et al.*, 2010a). There is *low confidence*  
25 (*limited evidence; medium agreement*) that climate change is threatening the temperate forest carbon sink directly or  
26 indirectly.

27  
28 At the biome level, there remains considerable uncertainty in the sign and the magnitude of the carbon cycle  
29 response of temperate forests to climate change. A comparison of DGVM models showed that for identical end of  
30 21<sup>st</sup> century climate projections, temperate forests are variously projected to substantially increase in total (biomass  
31 plus soil) carbon storage, especially as a result of potential gains in tree cover in eastern North America and Europe;  
32 or decrease due to reductions in total carbon storage per hectare and loss of tree cover (Sitch *et al.*, 2008).  
33 Projections for eastern Asia are less variable: temperate forests remain carbon sinks over the coming century, with  
34 carbon storage generally peaking by mid-century and then declining (He *et al.*, 2007; Sitch *et al.*, 2008; Ni, 2011;  
35 Peng *et al.*, 2009). However, regional vegetation models for China predict a substantial northward shift of temperate  
36 forest (Weng and Zhou, 2006; Ni, 2011). There is little indication from either models or observations that the  
37 responses of temperate forests to climate change are characterized by tipping points. The feedback mechanisms  
38 operating in boreal and tropical forests which lead to tipping point behavior appear to be less dominant in temperate  
39 forests (Bonan, 2008). There is *low confidence (medium evidence; low agreement)* on long-term, climate-driven  
40 changes in temperate forest biomass and geographical range shifts.

41  
42 At the species level, models predict that the potential climatic space for most tree species will shift poleward and up  
43 in altitude in response to climate change (Dale *et al.*, 2010; Ogawa-Onishi *et al.*, 2010; Hickler *et al.*, 2012).  
44 Associated long-term projected range shifts generally vary from several km to several tens of km per decade, most  
45 probably cannot achieve such high rates by natural migration (*e.g.* Chmura *et al.*, 2011, see also 4.3.2.5). Therefore,  
46 assisted migration has been suggested as an adaptation measure (see 4.4.2.4). Such shifts would alter biodiversity  
47 and ecosystem services from temperate forests (*e.g.* Dale *et al.*, 2010). Multi-model comparisons for temperate  
48 forests, however, illustrate that there are differences in species response and that models differ greatly in the severity  
49 of projected climate change impacts on species ranges (Kearney *et al.*, 2010; Kramer *et al.*, 2010; Morin and  
50 Thuiller, 2009; Cheaib *et al.*, 2012). Tree growth models project increased tree growth at the poleward and high  
51 altitudinal range limits over most of the next century in China (Ni, 2011). New approaches to modelling tree  
52 responses, based on the sensitivity of key life-history stages, suggest that climate change impacts on reproduction  
53 could be a major limitation on temperate tree distributions (Morin *et al.*, 2007). Comparisons with paleoecological  
54 data have helped improve confidence in the ability of models to project future changes in species ranges (Pearman *et*

1 *al.*, 2008, Allen *et al.*, 2010b, Garreta *et al.*, 2010). Model projections are qualitatively coherent with observations  
2 that temperate forest species are already moving up in altitude, probably due to climate warming at the end of the  
3 20th century (Lenoir *et al.*, 2008). There is *medium confidence (medium evidence; medium agreement)* that  
4 temperate tree and animal species are migrating poleward and upward altitudinally.  
5  
6

#### 7 4.3.3.1.3. Impacts of climate change on tropical wet and dry forests 8

9 The responses of tropical forests to variability and change in climate and atmospheric CO<sub>2</sub> concentration are  
10 superimposed upon the direct influences of human activities. Humans modify the composition and structure of  
11 tropical forests through the harvest of individual plants or animals and through management interventions to favor  
12 some species or structural features over others. Humans also convert forests to cropland or grazing land and  
13 influence forest exposure to ignition sources. Forest conversion is the best understood change that is underway in  
14 tropical forests. Climate change effects on tropical forests interact with the direct influences of humans and are  
15 understood largely through field studies of the responses of forests to extreme weather events and through models  
16 that are able to simulate a growing number of ecological and atmospheric processes.  
17

18 A key uncertainty in our understanding of future impacts of climate change on tropical forests is the strength of  
19 direct CO<sub>2</sub> effects on photosynthesis and transpiration (see section 4.3.2.4). These responses will play an important  
20 role in determining tropical forest trends as temperatures and atmospheric CO<sub>2</sub> concentrations rise. There is a  
21 physiological basis for arguing that photosynthesis will increase sufficiently to offset the inhibitory effects of higher  
22 temperatures on forest productivity (Lloyd and Farquhar, 2008) although heightened photosynthesis does not  
23 necessarily translate into an increase in overall forest biomass, (Körner and Basler, 2010). DGVMs and the current  
24 generation of Earth System Models, including those used within CMIP5 (e.g., Jones *et al.*, 2011) generally use  
25 formulations for CO<sub>2</sub> effects on photosynthesis and transpiration based on laboratory-scale work (Jarvis, 1976;  
26 Farquhar *et al.*, 1980; Ball *et al.*, 1987; Stewart, 1988; Collatz *et al.*, 1992; Leuning, 1995; Haxeltine and Prentice,  
27 1996; Cox *et al.*, 1998) that pre-dates larger ecosystem-scale studies, although some models have been optimized on  
28 the basis of more recent data (Jones *et al.*, 2011).  
29

30 A second important source of uncertainty is the rate of future CO<sub>2</sub> and temperature rise (Betts *et al.*, 2012).  
31 Modelled simulations of future climate in tropical forest regions indicate with *high confidence (robust evidence,*  
32 *high agreement)* that temperature will increase. Future precipitation change, in contrast, is highly uncertain and  
33 varies considerably between climate models (WG1 Annex A), although there is *medium confidence (medium*  
34 *evidence, medium agreement)* that some tropical regions, such as the eastern Amazon Basin, will experience lower  
35 precipitation (Malhi *et al.*, 2009b). The range of possible shifts in the moist tropical forest envelope is large,  
36 sensitive to the responsiveness of water use efficiency (WUE) to rising concentrations of atmospheric CO<sub>2</sub>, and  
37 varies depending on the climate and vegetation model that is used (Scholze *et al.*, 2006; Zelazowski *et al.*, 2011)  
38 (Sitch *et al.*, 2008) Recent model medley studies (Cox *et al.*, 2013; Huntingford *et al.*, 2013) indicate that the future  
39 geographical range of moist tropical forests as determined by its shifting climatological envelope is *less likely to*  
40 undergo major retractions or expansions by 2100 through climate change alone as previously predicted (Cox *et al.*,  
41 2000).  
42

43 Changes in the species composition and biomass of moist tropical forests observed in networks of long-term forest  
44 plots in moist tropical forests are generally consistent with increasing WUE associated with the rising concentration  
45 of CO<sub>2</sub>. Lianas and fast-growing tree species are increasing, as is forest biomass (Phillips *et al.*, 2002; Phillips *et al.*,  
46 2005; Lewis *et al.*, 2009a; Lewis *et al.*, 2009b; Lewis *et al.*, 2011). Faster tree growth could also result from changes  
47 in solar radiation and the ratio of diffuse to direct radiation (Mercado *et al.*, 2009; Lewis *et al.*, 2009a; Brando *et al.*,  
48 2010). There is *low confidence (limited evidence, medium agreement)* that the composition and biomass of Amazon  
49 and African forests are changing through the rise in atmospheric CO<sub>2</sub>. The potential suppression of photosynthesis  
50 and tree growth in tropical forests through rising air temperatures is supported by physiological and eddy covariance  
51 studies (Doughty and Goulden, 2008; Lloyd and Farquhar, 2008; Wood *et al.*, 2012), but is not yet observed as  
52 changes in forest biomass (except Clark *et al.*, 2003).  
53



1 Since AR4, there is new experimental and observational evidence of ecological thresholds of drought and fire in  
2 moist tropical forests that points to an important indirect role of climate change in driving large-scale changes in  
3 moist tropical forests (see Box 4-3). Forest tree mortality increased abruptly above a critical level of soil moisture  
4 depletion in two rainfall exclusion experiments (Nepstad *et al.*, 2007; Fisher *et al.*, 2008) and above a critical level  
5 of weather-related fire intensity in a prescribed burn experiment (Brando *et al.*, 2012). These experimental results  
6 were corroborated by observations of increased tree mortality during the extremely severe 2005 drought in the  
7 Amazon (Phillips *et al.*, 2009) and extensive forest fire (Alencar *et al.*, 2006; Aragão *et al.*, 2008; Alencar *et al.*,  
8 2011; Box 4-3). There is *medium confidence (medium evidence, high agreement)* that moist tropical forests have  
9 many tree species that are vulnerable to drought- and fire-induced mortality during extreme dry periods. There is  
10 *low confidence (limited evidence, low agreement)* that the severe droughts that have affected the Amazon region are  
11 associated with climate change (Shiogama *et al.*, 2011).

12  
13 There is also a growing body of evidence that severe weather events interact with land use to influence moist  
14 tropical forest fire regimes. Many moist tropical forests are not susceptible to fire during typical rainfall years  
15 because of high moisture content of fine fuels (Cochrane, 2003). Selective logging, drought, and fire itself can reduce  
16 this fire resistance by killing trees, thinning the canopy and allowing greater heating of the forest interior; Uhl and  
17 Kauffman, 1990; Ray *et al.*, 2005; Curran *et al.*, 2004; Box 4-3). Land use often increases the ignition sources in  
18 tropical landscapes (Silvestrini *et al.*, 2011). These relationships are not yet represented fully in coupled climate-  
19 vegetation models. There is *high confidence (robust evidence, high agreement)* that forest fire frequency and  
20 severity is increasing through the interaction between severe droughts and land use.

21  
22 There are an estimated one million square kilometres of dry tropical forests in the world (Miles *et al.*, 2006), defined  
23 as forests occurring in tropical regions characterized by pronounced seasonality in rainfall distribution (Mooney *et al.*,  
24 1995). More than half of the remaining tropical dry forests (54%) are located in South America. Approximately  
25 one third of the remaining tropical forests in the Americas are predicted to experience “severe climate change” by  
26 2055, defined as an increase in air temperature of at least 2.5 deg. C and/or a decrease in precipitation of at least 50  
27 mm a<sup>-1</sup>. Less than one fifth of forests in other tropical dry forest formations are faced with this level of climate risk  
28 (Miles *et al.*, 2006). Climate change, deforestation, fragmentation, fire, or human pressure place virtually all (97%)  
29 of the remaining tropical dry forests at risk (Miles *et al.*, 2006).

30  
31 \_\_\_\_\_ START BOX 4-3 HERE \_\_\_\_\_

### 32 33 **Box 4-3. A Possible Amazon Basin Tipping Point**

34  
35 Since AR4, our understanding of the potential of a large-scale, climate-induced, self-reinforcing transition of  
36 Amazon forests to a dry stable state (known as the Amazon “forest dieback”) has improved. Modeling studies  
37 indicate that the likelihood of a purely climate-driven dieback in 2100 is lower than previously thought (Malhi *et al.*,  
38 2009b; Good *et al.*, 2013; Cox *et al.*, 2013; Huntingford *et al.*, 2013) and there is now *medium confidence (robust  
39 evidence, medium agreement)* that climate change alone will not lead to widespread forest loss during this century.  
40 Meteorological fire danger is projected to increase (Golding and Betts, 2008; Betts *et al.*, submitted; Figure 4-8).  
41 Field studies and regional observations, have provided new evidence of critical ecological thresholds and positive  
42 feedbacks between climate change and land-use activities that could drive a fire-mediated, self-reinforcing dieback  
43 in this century. There is now *medium confidence (medium evidence, medium agreement)* that severe drought  
44 episodes, land use, and fire interact synergistically to drive the transition of mature Amazon forests to low-biomass,  
45 low-statured pyrophilic woody vegetation.

46  
47 Most primary forests of the Amazon Basin have damp fine fuel layers and low susceptibility to fire, even during  
48 annual dry seasons (Uhl and Kauffman, 1990; Ray *et al.*, 2005). Forest susceptibility to fire increases through  
49 canopy thinning and greater sunlight penetration caused by tree mortality associated with selective logging (Uhl and  
50 Kauffman, 1990; Ray *et al.*, 2005; Barlow and Peres, 2008), previous forest fire (Balch *et al.*, 2008; Brando *et al.*,  
51 2012), severe drought (Alencar *et al.*, 2006), or drought-induced tree mortality (Nepstad *et al.*, 2007; da Costa *et al.*,  
52 2010). The impact of fire on tree mortality is also weather-dependent. Under very dry, hot conditions, fire-related  
53 tree mortality can increase sharply (Brando *et al.*, 2012). Under some circumstances, tree damage is sufficient to  
54 allow light-demanding, flammable grasses to establish in the forest understory, increasing forest susceptibility to

1 further burning (Veldman and Putz, 2011). There is *high confidence (robust evidence, high agreement)* that logging,  
2 severe drought, and previous fire increase Amazon forest susceptibility to burning.

3  
4 Landscape level processes further increase the likelihood of forest fire. Ignition sources are more common in  
5 agricultural and grazing lands than in forested landscapes (Silvestrini *et al.*, 2011) (*high confidence: robust evidence,*  
6 *high agreement*), and forest conversion to grazing and crop lands can inhibit regional rainfall through changes in  
7 albedo and evapotranspiration (Costa *et al.*, 2007; Butt *et al.*, 2011; Knox *et al.*, 2011) (*low confidence: medium*  
8 *evidence, low agreement*) or through smoke, that can inhibit rainfall under some circumstances (Andreae *et al.*,  
9 2004) (*low confidence: medium evidence, low agreement*). Apart from these landscape processes, climate change  
10 could increase the incidence of severe drought episodes (Shiogama *et al.*, 2011).

11  
12 In sum, fire-mediated changes in Amazon forests are self-reinforcing through increases in tree mortality, forest  
13 susceptibility to fire, ignition sources, and regional rainfall inhibition (Figure 4-10). If current patterns of  
14 deforestation, logging, severe drought, and forest fire continue into the future, 55% of the region's forests will be  
15 cleared or degraded by 2030, even without invoking positive feedbacks with regional climate, releasing 20±10 Pg of  
16 carbon to the atmosphere (Nepstad *et al.*, 2008) (*low confidence: low evidence, medium agreement*). The likelihood  
17 of a tipping point being reached may decline if extreme droughts (such as 1998, 2005, and 2010) (Marengo *et al.*,  
18 2011) become less frequent, if land management fires are suppressed, if forest fires are extinguished (Soares-Filho *et*  
19 *al.*, 2012), if deforestation declines, or if cleared lands are reforested (Nepstad *et al.*, 2008). The 76% decline in  
20 deforestation in the Brazilian Amazon with 80% of the region's forest still standing (INPE, 2012) demonstrates that  
21 large-scale mitigation of a fire-mediated tipping point could be feasible.

22  
23 [INSERT FIGURE 4-10 HERE

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

30  
31 \_\_\_\_\_ END BOX 4-3 HERE \_\_\_\_\_  
32  
33

#### 34 4.3.3.2. Rangelands and Drylands, including Mediterranean-type Systems

35  
36 The following sections treat a wide range of terrestrial ecosystems covering a large part of the terrestrial surface,  
37 whose unifying features are that they are not classified as forests and they typically exhibit strong water stress for  
38 several months each year. Grasses, grass-like plants and herbs are usually a major part of their vegetation cover. The  
39 principle land use often involves either wild or domestic herbivores.

##### 40 41 42 4.3.3.2.1. Savannas

43  
44 Savannas are defined as mixtures of coexisting trees and grasses. The geographical distribution of tropical savannas  
45 is determined by temperature, the seasonal availability of water, fire and soil conditions (Ellery *et al.*, 1991; Walker  
46 and Langridge, 1997; Staver *et al.*, 2011) and is therefore inferred to be susceptible to climate change. The  
47 proportion of trees and grasses in savannas is considered inherently unstable under some conditions (DeMichele *et*  
48 *al.*, 2011; Staver *et al.*, 2011; Wake, 2012). Savannas are characterized by annual to decadal fires of relatively low  
49 intensity, which are an important factor in maintaining the tree-grass proportions (Beerling and Osborne, 2006), but  
50 also constitute a major global source of pyrogenic emissions from land to atmosphere (Schultz *et al.*, 2008; van der  
51 Werf *et al.*, 2010). The differential effects of climate change, rising CO<sub>2</sub>, fire and herbivory on trees and grasses  
52 have the potential to alter the structure, composition and ecosystem service delivery capacity of mixed tree-grass  
53 systems (e.g. Hughes *et al.*, 2006). Since tropical savannas occupy about an eighth of the global land surface, and

1 mixed tree-grass systems outside the tropics cover a similar area, small changes in their structure or fire regime can  
2 have globally-significant effects on the emission or uptake of radiatively-active gases and particles.  
3

4 There is evidence from many parts of the world that the tree cover and biomass in savannas has increased over the  
5 past century and in some places, on all continents, continues to do so (*high agreement, robust evidence*: Cabral *et al.*,  
6 2009; Angassa and Oba, 2008; Moleele *et al.*, 2002; Wigley *et al.*, 2009; Witt *et al.*, 2009; Lunt *et al.*, 2010;  
7 Rohde and Hoffman, 2012). The general consequences are more carbon stored per unit land area as tree biomass and  
8 soil organic matter (Hughes *et al.*, 2006; Liao *et al.*, 2006; Knapp *et al.*, 2007; Throop and Archer, 2008; Boutton *et al.*,  
9 2009), changes in hydrology (Muñoz-Robles *et al.* 2011) and reduced grazing potential (Scholes and Archer,  
10 1997). Increasing tree cover in savannas has been attributed to changes in land management (Joubert *et al.*, 2008;  
11 Van Auken, 2009), rising CO<sub>2</sub> (Bond and Midgley, 2012; Buitenwerf *et al.*, 2012), climate variability and change  
12 (Eamus and Palmer, 2008; Fensham *et al.*, 2009) or two or more of these factors acting in combination (Ward, 2005;  
13 Bond *et al.*, 2008). As yet there are no studies that definitively attribute the relative importance of the various causes  
14 of woody plant biomass increase in savannas and grasslands, but there is *medium agreement* and *robust evidence*  
15 that climate and atmospheric changes are contributing factors in many cases. The increased growth rate of C3 trees  
16 relative to C4 grasses under by rising CO<sub>2</sub> could relieve the demographic bottleneck that keeps trees trapped within  
17 the flame zone of the grasses, a hypothesis supported by elevated CO<sub>2</sub> experiments with savanna saplings (Kgope *et al.*,  
18 2010). A vegetation model of grasslands, savannas and forests suggests that rising CO<sub>2</sub> does increase the  
19 likelihood of abrupt shifts to woodier states, but the transition will take place at different CO<sub>2</sub> concentrations in  
20 different environments (Higgins and Scheiter, 2012). On the other hand, observation of contrasts in the degree of  
21 savanna thickening between land parcels with the same CO<sub>2</sub> exposure but different land use histories, topographic  
22 position or soil depth (Wu and Archer, 2005; Wiegand *et al.*, 2005) imply that land management, water balance and  
23 microclimate are also important. Tree cover in savannas is rainfall-constrained (Sankaran *et al.*, 2005), suggesting  
24 that increases in rainfall could lead to increased tree biomass. In some places the savanna boundary is moving into  
25 former grasslands on elevation or climate gradients (Breshears, 2006).  
26

27 It has been projected that drying and greater seasonality, acting in conjunction with increased fire, could lead to  
28 more savanna-like conditions in parts of the Amazon basin (Malhi *et al.*, 2009a; Box 4-3). In parts of Central Africa,  
29 forests have been observed to be moving into adjacent savannas and grasslands (Mitchard *et al.*, 2009), possibly due  
30 to depopulation and fire changes. In northern Australia, forest is expanding into former savanna areas (Brook and  
31 Bowman, 2006; Tng *et al.*, 2012; Bowman *et al.*, 2011  
32  
33

#### 34 4.3.3.2.2. *Grasslands and shrublands* 35

36 Much evidence from around the world shows that dry grasslands and shrublands are highly responsive in terms of  
37 primary production, species composition and carbon balance to changes in water balance (precipitation and  
38 evaporative demand) within the range of projected climate changes (e.g., Sala *et al.*, 1988; Snyman and Fouché,  
39 1993; Fay *et al.*, 2003; Peñuelas *et al.*, 2004, 2007; Prieto *et al.*, 2009; Wu and Chen, 2013) Other factors being  
40 equal, grasslands and shrublands in cool areas are expected to respond to warming with increased primary  
41 production, while those in hot areas are expected to show decreased production. Grasslands are exposed to rising  
42 CO<sub>2</sub>, which is postulated to stimulate plant production, but more so for temperate grasses, herbs and woody plants  
43 with a C3 photosynthetic system than for C4 tropical grasses (see section 4.2.4.4). Some grasslands are  
44 simultaneously exposed to elevated levels of nitrogen deposition, which alters species composition, increases  
45 primary production up to a point and decreases it thereafter (see section 4.2.4.2, Bobbink *et al.*, 2010; Cleland and  
46 Harpole, 2010). Most rangelands are subject to grazing and fire. All these factors may have interactive effects, and  
47 species composition changes may overwhelm or alter the physiological climate effects (Suttle *et al.*, 2007).  
48

49 Drawing on published studies, Ravi *et al.* (2010) found that changing climate and land use have resulted in increased  
50 aridity and a higher frequency of droughts in drylands around the world. They predict increasing dominance of  
51 abiotic controls of land degradation (in contrast to direct human- or herbivore-driven degradation); in particular  
52 highlight changes in hydrology and the erosion of soil by wind.  
53

1 Rainfall amount and timing have large effects on a wide range of biological processes in grasslands and shrublands,  
2 including seed germination, seedling establishment, plant growth, flowering time, root mass, community  
3 composition, population and community dynamics production, decomposition and respiration, microbial processes  
4 and carbon assimilation (e.g. Peñuelas *et al.*, 2004, 2007; Beier *et al.*, 2008; Sowerby *et al.*, 2008; Albert *et al.*,  
5 2011; Albert *et al.*, 2012; Miranda *et al.*, 2009; Selsted *et al.*, 2012; Walter *et al.*, 2012). In a controlled experiment  
6 with communities of tallgrass prairie species in Kansas, Fay *et al.* (2008) showed that changes in the interval  
7 between rainfall events and the rainfall delivered by individual storms altered carbon assimilation and respiration  
8 rates independently of changes in the total amount of water supplied. A similar experiment on a Mediterranean  
9 semiarid grassland community (Miranda *et al.*, 2009) found that delayed watering led to decreases in plant  
10 productivity and to delayed flowering. Species diversity was not affected by delayed onset of rain; however, it was  
11 reduced by changes in the frequency, amount and seasonality of wetting. In the Mongolian steppe (Shinoda *et al.*,  
12 2010), drought reduced the above ground plant mass but did not substantially affect the root mass. A subset of  
13 species did not recover to pre-drought levels once precipitation returned to normal levels. A water and temperature  
14 manipulation experiment in China indicated that changes in water balance had a stronger effect on grassland  
15 microbial processes leading to carbon storage than changes in temperature (Liu *et al.*, 2009). Engler *et al.* (2011)  
16 emphasized that precipitation changes were as important for mountain flora in Europe as temperature changes, and  
17 the greatest composition changes will probably occur when decreased precipitation accompanies warming. Vohland  
18 and Barry (2009) reviewed the effectiveness of in situ rainwater harvesting (RWH) as an adaptation to climate  
19 change in sub-Saharan Africa and concluded that it conferred higher food security and income, but may strengthen  
20 conflicts between nomadic and sedentary populations.

21  
22 Experimental manipulation of six European shrublands on a latitudinal gradient showed the response to warming  
23 and drought to depend on site, year and plant species (Peñuelas *et al.*, 2004, 2007). Droughts decreased aboveground  
24 net primary production two thirds of the sites. Responses to warming were weaker in the presence of aridity. Gao  
25 and Giorgi (2008) identified the southern Mediterranean as particularly vulnerable to water stress and desertification  
26 processes under climate change conditions. Analyzing 168 site-years of eddy covariance measurements, Wu and  
27 Chen (2013) found summer drought to reduce both summer gross primary production and net ecosystem production  
28 in grasslands and crops of North America.

29  
30 A European gradient study (Emmett *et al.*, 2004), showed that N mineralization in shrublands under either arid or  
31 wet conditions is more sensitive to periodic droughts than systems under more mesic conditions. An increase in  
32 drought frequency, without an increase in drought severity, leads to loss of soil carbon in moist, carbon-rich  
33 moorlands, due to changes in soil structure or soil microbial community leading to increased hydrophobicity and soil  
34 respiration (Sowerby *et al.*, 2008, 2010). Responses of shrublands to drought may partly be driven by changes in the  
35 soil microbial community (Jensen *et al.*, 2003) or changes in soil fauna (Maraldo *et al.*, 2008).

36  
37 Beier *et al.* (2008) found that nitrogen limitation reduces acclimation in plant production, as a result of an  
38 asymmetrical response to warming between the carbon and nitrogen cycles. Decreased tissue concentrations of  
39 phosphorus was also associated with warming and drought (Peñuelas *et al.*, 2004; Beier *et al.*, 2008; Peñuelas *et al.*,  
40 2012). strong interactions of warming with disturbances have been observed leading to increased nitrogen leaching  
41 from shrubland ecosystems (Beier *et al.*, 2004).

42  
43 N fertilization and nighttime warming caused soil and plant community responses within one season in a  
44 Chihuahuan semi-arid desert (Collins *et al.*, 2010). In contrast, Grime *et al.* (2008) found little species composition  
45 change after 13 years of manipulation of water and temperature in an infertile grassland in England. The community  
46 composition of subalpine grasslands in Switzerland have changed relatively little over the past fifty years (Vittoz *et al.*,  
47 2009). The changes that did occur were largely associated with changes in land management rather than climate,  
48 although they were consistent with warming trends.

49  
50 Sommer *et al.* (2010) used global empirical relationships between plant species richness and climate variables such  
51 as temperature, moisture and radiation to project richness changes under future climates. This method is independent  
52 of the usual species-by-species or biome-based climate niche approach, but its predictions apply to the long-term  
53 equilibrium outcome, rather than changes in the next few decades. In most temperate and arctic regions, the capacity

1 to support richer (i.e. more diverse) communities increases with rising temperature, while the projections indicate a  
2 strong decline in capacity to support species-rich communities in most tropical and subtropical regions.  
3

4 Many grasslands, shrublands and savannas are characterized by relatively frequent but low-intensity fires.  
5 The fire frequency, intensity and seasonality in southern Africa are primarily under climate control, and secondarily  
6 influenced by management (Archibald *et al.*, 2009). In South America, El Niño-Southern Oscillation climate modes  
7 strongly influence on area burned in Colombian grasslands (Armenteras-Pascual *et al.*, 2011). Fire frequency in  
8 grasslands and forests in Australia is projected to increase, due to climate change (Pitman *et al.*, 2007). Since it is  
9 well-established that plant species composition is sensitive to the fire regime (e.g. Gibson and Hulbert, 1987; Uys *et al.*,  
10 2004; Gill *et al.*, 1999 and many other studies) this provides an indirect mechanism by which climate change can  
11 lead to species composition change in grasslands and rangelands.  
12

13 Relatively little is known regarding the combined effect of climate change, other global change factors and  
14 increasing use pressure by large mammal herbivores in rangelands, nor on the consequences for pastoral livelihoods  
15 that depend on rangelands (Thornton *et al.*, 2009).  
16

#### 17 18 4.3.3.2.3. *Deserts* 19

20 The deserts of the world, defined as land areas with an arid or hyperarid climate regime, occupy 35 % of the global  
21 land surface. Deserts are sparsely populated, but the people who do live there are amongst the poorest in the world  
22 (Millennium Ecosystem Assessment, 2005b). There is *medium agreement* but *limited evidence* that the present  
23 extent of deserts will increase in the coming decades, despite the projected increase in rainfall at a global scale, as a  
24 result of the strengthening of the Hadley circulation. The descending air on the poleward side of the Hadley  
25 circulation results in decreased rainfall (Mitas and Clement, 2005; Seidel *et al.*, 2008; Johanson and Fu, 2009; Lu *et al.*,  
26 2009; Zhou *et al.*, 2011) and which determines the location of the broad band of warm deserts lands  
27 approximately 15-30° N and S of the equator. Recent satellite data show a greening trend in the Sahel, associated  
28 with a return to wetter climates following a multidecade dry spell. There may be a feedback to the global climate  
29 from an increase in desert extent (Alkama *et al.*, 2012), which differs in sign between deserts closer to the equator  
30 than 20° and those closer to the poles. In model simulations, extension of the ‘warm deserts’ causes warming, while  
31 extension of the ‘cold deserts’ causes cooling, in both cases largely through albedo-mediated effects. Two special  
32 circumstances of desert areas are important with respect to climate change. Deserts are expected to become warmer  
33 and drier at faster rates than other terrestrial regions (Lapola *et al.*, 2009). Most deserts are already extremely hot,  
34 and therefore further warming will probably be physiologically injurious rather than beneficial. Secondly, the  
35 ecological dynamics in deserts are rainfall event-driven (Holmgren *et al.*, 2006), often involving the concatenation  
36 of a number of quasi-independent events. According to a conceptual model elaborated by Lapola *et al.* (2009) some  
37 desert tolerance mechanisms (e.g., biological adaptations by long-lived taxa) may be outpaced by global climate  
38 change.  
39

40 Deserts are expected to become warmer and drier at a faster rate than other terrestrial regions (Stahlschmidt *et al.*,  
41 2011). The warm deserts are already extremely hot, and therefore further warming is generally physiologically  
42 injurious rather than beneficial. Ecological dynamics in deserts are rainfall event-driven (Holmgren *et al.*, 2006),  
43 often involving the concatenation of a number of quasi-independent events. According to a conceptual model  
44 elaborated by Stahlschmidt *et al.* (2011) some desert tolerance mechanisms (e.g., biological adaptations by long-  
45 lived taxa) may be outpaced by global climate change.  
46

#### 47 48 4.3.3.3. *Rivers, Lakes, Wetlands and Peatlands* 49

50 Freshwater ecosystems are considered to be among the most threatened on the planet (Dudgeon *et al.*, 2006;  
51 Vörösmarty *et al.*, 2010). Fragmentation of rivers by dams and the alteration of natural flow regimes have led to  
52 major impacts on freshwater biota (Pringle, 2001, Bunn and Arthington, 2002; Nilsson *et al.*, 2005). Floodplains and  
53 wetland areas have become occupied for intensive urban and agricultural land use to the extent that many are  
54 functionally extinct from their rivers (Tockner *et al.*, 2008). Pollution from cities and agriculture, especially nutrient

1 loading, has resulted in declines in water quality and the loss of essential ecosystem services (Allan, 2004). As a  
2 direct consequence of these and other impacts, freshwater systems have the highest rates of extinction of any  
3 ecosystem (as much as 4% pa for some groups - e.g. crayfish, mussels, fishes and amphibians in North America),  
4 with estimates that at least 10,000-20,000 freshwater species are extinct or at risk (Strayer and Dudgeon, 2010). This  
5 is particularly significant considering that freshwater habitats support 6% of all described species, including  
6 approximately 40% of fish diversity and a third of the vertebrate diversity (Dudgeon *et al.*, 2006; Balian *et al.*,  
7 2008).

8  
9 Peatlands contain large stocks of carbon that are vulnerable to change through land use and climate change.  
10 Although peatlands cover only about 3% of the land surface, they hold the equivalent of half of the atmosphere's  
11 carbon (as CO<sub>2</sub>), or one third of the world's soil carbon stock (Limpens *et al.*, 2008; Page *et al.*, 2011). About 14-  
12 20% of the world's peatlands are currently used for agriculture (Oleszczuk *et al.*, 2008) and many, particularly peat  
13 swamp forests in Southeast Asia, are still undergoing major transformations through drainage and burning in  
14 preparation for oil palm and other crops or through unintentional burning (Limpens *et al.*, 2008; Hooijer *et al.*,  
15 2010). Deforestation, drainage, and burning in Indonesian peat swamp forests can release 1,400 Mg CO<sub>2</sub> ha<sup>-1</sup>  
16 (Murdiyarso *et al.*, 2010), contributing significantly to global GHG emissions, especially during periods of intense  
17 drought associated with ENSO when burning is more common (Page *et al.*, 2002). Anthropogenic disturbance has  
18 changed peatlands from being a weak global carbon sink to a source (Frolking *et al.*, 2011) with large inter-annual  
19 variability.

20  
21 It is *very likely* that these stressors to freshwater ecosystems and peatlands will continue to dominate as human  
22 demand for water resources grows, accompanied by increased urbanization and intensification of agriculture  
23 (Vörösmarty *et al.*, 2000; Malmqvist *et al.*, 2007; Dise, 2009). However, climate change will have significant  
24 additional impacts on freshwater ecosystems (*high confidence*), from altered thermal regimes, altered precipitation  
25 and flow regimes and, in the case of coastal wetlands, sea level rise. Specific aquatic habitats that are most  
26 vulnerable to these direct climate effects, especially rising temperatures, are those at high altitude and high latitude,  
27 including arctic and subarctic bog communities on permafrost, and alpine and arctic streams and lakes (see 4.3.4.4;  
28 Smith *et al.*, 2005; Smol and Douglas, 2007a). It is noteworthy that these high latitude systems currently experience  
29 a relatively low level of threat from other human activities (Vörösmarty *et al.*, 2010). Dryland rivers and wetlands,  
30 many already experiencing severe water stress from human consumptive use, are also *likely* to be further impacted  
31 by decreased and more variable precipitation and higher temperatures. Headwater stream systems in general are also  
32 vulnerable to the effects of warming because their temperature regimes closely track air temperatures (Caissie,  
33 2006).

34  
35 Evidence of rising stream and river temperatures over the past few decades across several continents continues to  
36 grow (Chessman, 2009; Kaushal *et al.*, 2010; Langan *et al.*, 2001; Morrison *et al.*, 2002; Ormerod, 2009; van Vliet  
37 *et al.*, 2011; Webb and Nobilis, 2007), and has been linked by observational and experimental studies to shifts in  
38 invertebrate community composition, including declines in cold stenothermic species (Brown *et al.*, 2007;  
39 Chessman, 2009; Durance and Ormerod, 2007; Ormerod, 2009). Rising water temperatures are also implicated in  
40 changes in the composition of river fish communities (Buisson *et al.*, 2008; Daufresne and Boet, 2007), especially in  
41 headwater streams where species are more sensitive to warming (e.g. Buisson and Grenouillet, 2009), and this will  
42 probably restrict the distribution of cool-water species such as salmonids within their current range (Bartholow,  
43 2005; Bryant, 2009; Ficke *et al.*, 2007; Hague *et al.*, 2011). While these changes in river temperature regimes may  
44 also open up new habitat at higher latitudes (or altitudes) for migratory (Reist *et al.*, 2006) and cool- and warm water  
45 species of fish (Tisseuil *et al.*, 2012), there is *high confidence* that range contraction threatens the long term  
46 persistence of some fully aquatic species, including mountain-top endemics; e.g. species of spiny crayfish  
47 (Parastacidae: *Eustacus*) in eastern Australia (Ponniah and Hughes, 2004).

48  
49 The surface and epilimnetic waters in many lakes also show increases in temperature over the past four decades,  
50 with warming trends detected in North America, Eurasia and Africa (Adrian *et al.*, 2009). Rising temperatures  
51 resulting in early onset and increased duration and stability of the thermocline in temperate lakes during summer  
52 (Winder and Schindler, 2004) are projected to favor a shift in dominance to smaller phytoplankton (Parker *et al.*,  
53 2008; Yvon-Durocher *et al.*, 2011) and cyanobacteria (Johnk *et al.*, 2008; Paerl *et al.*, 2011; Wiedner *et al.*, 2007),  
54 especially in those ecosystems experiencing high anthropogenic loading of nutrients (Wagner and Adrian, 2009);

1 with impacts to water quality, food webs and productivity (Gyllström *et al.*, 2005; O'Reilly *et al.*, 2003; Parker *et al.*,  
2 2008; Shimoda *et al.*, 2011; Verburg *et al.*, 2003). Emergent aquatic macrophytes are likely to expand their  
3 northward distribution and percentage cover in boreal lakes and wetlands, posing an increasing overgrowth risk for  
4 sensitive macrophyte species (Alahuhta *et al.*, 2011). Long-term shifts in macroinvertebrate communities have also  
5 been observed in European lakes where temperatures have increased (Burgmer *et al.*, 2007), noting that warming  
6 may increase species richness in smaller temperate waterbodies, especially those at high altitude (Rosset *et al.*,  
7 2010). While less studied, it has been proposed that tropical ectotherms will be particularly vulnerable because they  
8 will approach critical maximum temperatures proportionately faster than species in high latitude environments,  
9 despite lower rates of warming (Deutsch *et al.*, 2008; Hamilton, 2010; Laurance *et al.*, 2011).

10  
11 There is growing evidence that climate induced changes in precipitation will significantly alter ecologically  
12 important attributes of hydrologic regimes in rivers and wetlands, and exacerbate impacts from human water use in  
13 developed river basins (see Box CC-RF; Aldous *et al.*, 2011; Xenopoulos *et al.*, 2005). Freshwater ecosystems in  
14 Mediterranean-montane ecoregions (e.g. Australia, California and South Africa), are projected to experience a  
15 shortened wet season and prolonged, warmer summer season (Klausmeyer and Shaw, 2009), increasing the  
16 vulnerability of fish communities to drought (Magalhães *et al.*, 2007; Hermoso and Clavero, 2011) and floods  
17 (Meyers *et al.*, 2010). Shifts in hydrologic regimes in snow-melt systems, including earlier runoff and declining base  
18 flows in summer (Stewart *et al.*, 2005; Stewart, 2009), are projected to impact on freshwater ecosystems, through  
19 changes in physical habitat and water quality (Bryant, 2009). Declining rainfall and increased inter-annual  
20 variability will probably increase low-flow and dry-spell duration in dryland regions, leading to reduced water  
21 quality in remnant pools (Dahm *et al.*, 2003), reduction in floodplain egg- and seed-banks (Capon, 2007; Jenkins  
22 and Boulton, 2007), the loss of permanent aquatic refugia for fully aquatic species and water birds (Bond *et al.*,  
23 2008; Johnson *et al.*, 2005; Sheldon *et al.*, 2010), and terrestrialization of wetlands (Davis and Thompson, 2010).

24  
25 Climate induced changes in precipitation will probably be an important factor altering peatland vegetation in  
26 temperate and boreal regions, with decreasing wetness during the growing season generally associated with a shift  
27 from a *Sphagnum* dominated to vascular plant dominated vegetation type and a general decline of C sequestration in  
28 the longer term (Limpens *et al.*, 2008). Mire ecosystems (i.e. bogs, transition bogs and fens) in central Europe face  
29 severe climate risk, with increased summer temperatures being particularly important (Essl *et al.*, 2012). Declines in  
30 precipitation and longer dry seasons in major tropical peatland areas in southeast Asia, are projected to result in  
31 lower water tables more often and for longer periods, with an increased risk of fire (Li *et al.*, 2007; Rieley *et al.*,  
32 2008; Froking *et al.*, 2011).

33  
34 Sea level rise will lead to direct losses of coastal wetlands with associated impacts on waterbirds and other wildlife  
35 species dependent on fresh water (BMT WBM, 2010; Pearlstine *et al.*, 2010; Traill *et al.*, 2010) but the impact will  
36 probably be relatively small compared with the degree of direct and indirect human-induced destruction (Nicholls,  
37 2004). River deltas and associated wetlands are particularly vulnerable to rising sea level, and this threat is further  
38 compounded by trapping of sediment in reservoirs upstream and subsidence from removal of oil, gas and water  
39 (Syvitski *et al.*, 2009; see Chapter 5.3.1.4). Lower river flows might exacerbate the impact of sea level rise and thus  
40 salinization on freshwater ecosystems close to the ocean (Ficke *et al.*, 2007).

#### 43 4.3.3.4. Tundra, Alpine, Permafrost Systems

44  
45 The region of the High Arctic, and its tundra-dominated landscapes, has warmed more than the global average over  
46 the last century (Kaufman *et al.*, 2009; Hartmann *et al.*, in press. Changes consistent with warming are also evident  
47 in the freshwater systems, ecosystems (both plants and animals) and permafrost of the region (Hinzman *et al.*, 2005;  
48 Axford *et al.*, 2009; Jia *et al.*, 2009b; Post *et al.*, 2009; Prowse and Brown, 2010; Romanovsky *et al.*, 2010; Walker  
49 *et al.*, 2012). Change is widespread, with most of the Arctic experiencing recent change in vegetation  
50 photosynthetic capacity and other aspects, particularly in areas adjacent to areas of the Arctic with rapidly retreating  
51 sea ice (Bhatt *et al.*, 2010).

52  
53 There is *high confidence* that continued climate change is projected to cause the terrestrial vegetation and lake  
54 systems of the Arctic to change substantially in the future, with an ongoing expansion in woody vegetation cover

1 projected in tundra regions over the 21<sup>st</sup> Century in the CMIP5 Earth System Models (Ciais *et al.*, in press) by  
2 dynamic global vegetation models driven by other climate model projections, and by observationally-based  
3 statistical models (Pearson *et al.*, 2013). Changes may be complex (see Box 4-4) and in some cases involve non-  
4 linear and threshold responses to warming and other climatic change (Hinzman *et al.*, 2005; Mueller *et al.*, 2009b;  
5 Bonfils *et al.*, 2012). Due to long response times of vegetation to both warming and increased CO<sub>2</sub> (Ciais *et al.*, in  
6 press; Falloon *et al.*, 2012) Earth System Models project Arctic vegetation change to continue long after any  
7 stabilization of global mean temperature. In some regions, reduced surface albedo due to increased vegetation cover  
8 is projected to cause further local warming even in scenarios of stabilized global radiative forcing due to greenhouse  
9 gases (Falloon *et al.*, 2012).

10  
11 In the arctic tundra biome, vegetation productivity has systematically increased over the past few decades, as  
12 documented across a range of scales in both North America and northern Eurasia – from the plot level (Myers-Smith  
13 *et al.*, 2011; Elmendorf *et al.*, 2012) to the region (Stow *et al.*, 2007) to continental (Jia *et al.*, 2009b) and the  
14 circumpolar arctic (Goetz *et al.*, 2007; de Jong *et al.*, 2011). This phenomenon is amplified by retreat of coastal sea  
15 ice (Bhatt *et al.*, 2010) and has been widely discussed in the context of increased shrub growth consistent with  
16 documented shrub expansion over the last half century through repeat photography and satellite observations  
17 (Forbes *et al.*, 2010; Myers-Smith *et al.*, 2011). Deciduous shrubs (i.e., dwarf birch, alder and willow species), in  
18 particular, respond to warming with increased growth (Euskirchen *et al.*, 2009; Lantz *et al.*, 2010), but this response  
19 is shared with other plant functional types, particularly graminoids (Walker, 2006; Epstein, 2008). Analyses of  
20 satellite time series data show the increased productivity trend is not unique to shrub-dominated areas (Jia *et al.*,  
21 2009b; Beck and Goetz, 2011), thus greening is a response shared by multiple vegetation communities and  
22 continued changes in the tundra biome can be expected irrespective of shrub presence. Shrub expansion and height  
23 changes remain particularly important, however, because they trap snow, mediate winter soil temperature and  
24 summer moisture regimes, increase nutrient mineralization, and produce a positive feedback for additional shrub  
25 growth (Sturm *et al.*, 2005; Lawrence *et al.*, 2007; Bonfils *et al.*, 2012). Although increased shrub cover and height  
26 produce shadowing that reduce ground heat flux and active layer depth, they also reduce surface albedo, increase  
27 energy absorption and evapotranspiration (Chapin III *et al.*, 2005; Blok *et al.*, 2010), and produce feedbacks that  
28 reinforce shrub densification and regional warming (Lawrence and Swenson, 2011; Bonfils *et al.*, 2012). On  
29 balance, these feedbacks can act to partially offset one another, but when coupled with warmer and wetter conditions  
30 they act to increase active layer depth and permafrost thaw (Yi *et al.*, 2007; Bonfils *et al.*, 2012).

31  
32 The arctic tundra biome is also experiencing shifts in two additional phenomena; fire disturbance and permafrost  
33 degradation. Both of these processes facilitate conditions for woody species establishment in tundra areas, either  
34 through incremental migration or via more rapid “leap-frogging” to areas reinitialized by burning (Epstein *et al.*,  
35 2007; Goetz *et al.*, 2011). When already present at the boreal-tundra ecotone, even sparsely, shrub and tree species  
36 show increased productivity with warmer conditions (Devi *et al.*, 2008; Andreu-Hayles *et al.*, 2011; Elmendorf *et al.*,  
37 2012). Tundra fires not only emit large quantities of combusted carbon formerly stored in vegetation and organic  
38 soils (Mack *et al.*, 2011; Rocha and Shaver, 2011) but also increase active layer depth during summer months  
39 (Racine *et al.*, 2004; Liljedahl *et al.*, 2007) and produce thermokarsting associated with thawing of ice-rich  
40 permafrost. There is tremendous variability in the degree of thermokarsting associated with fire disturbance,  
41 depending upon the substrate and ice content (Jorgenson *et al.*, 2010) but the combination of thermokarsting and  
42 seasonal cryoturbation create conditions that alter vegetation succession (Racine *et al.*, 2004; Lantz *et al.*, 2009;  
43 Higuera *et al.*, 2011).

44  
45 There is *high confidence* that the area of permafrost is projected to continue to decline over the first half of the 21<sup>st</sup>  
46 Century in all emissions scenarios (Figure 4-11). In the RCP2.6 scenario of an early stabilization of CO<sub>2</sub>  
47 concentrations, permafrost area is projected to stabilize at a level approximately 20% below the 20<sup>th</sup> Century area,  
48 and then begin a slight recovering trend. In RCP4.5, in which CO<sub>2</sub> concentration is stabilized at approximately  
49 550ppmv by the mid-21<sup>st</sup> Century, permafrost continues to decline for at least another 250 years. In the RCP8.5  
50 scenario of ongoing CO<sub>2</sub> rise, permafrost area is simulated to approach zero by the middle of the 22<sup>nd</sup> Century  
51 (Figure 4-11).



1 [INSERT FIGURE 4-11 HERE

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

5  
6 Frozen soils and permafrost currently hold more than twice the carbon than the atmosphere and thus represent a  
7 particularly large vulnerability to climate change (i.e., warming). Although the Arctic is currently a net carbon sink,  
8 continued warming will act to soon turn the Arctic to a net carbon source, that will in turn create a potentially strong  
9 positive feedback to accelerate Arctic (and global) warming with additional releases of CO<sub>2</sub>, CH<sub>4</sub>, and perhaps N<sub>2</sub>O,  
10 from the terrestrial biosphere into the atmosphere (Schuur *et al.*, 2008; Schuur *et al.*, 2009; Maslin *et al.*, 2010;  
11 McGuire *et al.*, 2010; O'Connor *et al.*, 2010; Schaefer *et al.*, 2011). Moreover, this feedback is already accelerating  
12 due to climate-induced increases in fire (McGuire *et al.*, 2010; O'Donnell *et al.*, 2011). The rapid retreat of  
13 snowcover, and resulting spread of shrubs and trees into areas currently dominated by tundra has also already begun,  
14 and will continue to serve as a positive feedback accelerating high latitude warming (Chapin III *et al.*, 2005; Bonfils  
15 *et al.*, 2012).

16  
17 There is *medium confidence* that rapid change in the Arctic is also affecting its animals. For example, seven of 19  
18 sub-populations of the polar bear are declining in number, while four are stable, one is increasing and the remaining  
19 seven have insufficient data to identify a trend (Vongraven and Richardson, 2011). Declines of two of the sub-  
20 populations are linked to reductions in sea ice (Vongraven and Richardson, 2011). Polar bear populations are  
21 projected to decline greatly in response to continued Arctic warming (Hunter *et al.*, 2010), and it is expected that the  
22 populations of other Arctic animals (e.g., fox and caribou) will be affected dramatically by climate change (Post *et al.*,  
23 2009; Sharma *et al.*, 2009). Simple niche-based, or climatic envelope models have difficulty in capturing the full  
24 complexity of these future changes (MacDonald, 2010).

25  
26 There is *high confidence* that alpine systems are already showing a high sensitivity to on-going climate change and  
27 will be highly vulnerable to change in the future. In western North America, warming, glacier retreat, snowpack  
28 decline and drying of soils is already causing a large increase in mountain forest mortality, wildfire and other  
29 ecosystem impacts (e.g., Westerling *et al.*, 2006; Kelly and Goulden, 2008; Crimmins *et al.*, 2009; van Mantgem *et al.*,  
30 2009; Pederson *et al.*, 2010; Muhlfeld *et al.*, 2011; Schwilk and Keeley, 2012; Park Williams *et al.*, 2012), and  
31 disturbance will continue to be an important agent of climate-induced change in this region (Littell *et al.*, 2010).

32 Alpine ecosystems already appear to already be changing in response to climate change in Africa, Tibet, the Alps,  
33 the tropics and elsewhere (Cannone *et al.*, 2007, 2008; Lenoir *et al.*, 2008, 2010; Cui and Graf, 2009; Britton *et al.*,  
34 2009; Normand *et al.*, 2009; Chen *et al.*, 2009, 2011; Allen *et al.*, 2010a; Eggermont *et al.*, 2010; Kudo *et al.*, 2011;  
35 Laurance *et al.*, 2011; Engler *et al.*, 2011; Dullinger *et al.*, 2012). For example, in a study of permanent plots from  
36 1994 to 2004 in the Austrian high Alps, a range contraction of subnival to nival vascular plant species was indicated  
37 at the downslope edge, and an expansion of alpine pioneer species at the upslope edge (Pauli *et al.*, 2007).

38 Thermophilous vascular plant species were observed to colonize in alpine mountain-top vegetation across Europe  
39 during the past decade (Gottfried *et al.*, 2012). As with the Arctic, permafrost thawing in alpine systems could  
40 provide a strong positive feedback in those systems (e.g., Tibet; Cui and Graf, 2009).

41 \_\_\_\_\_ START BOX 4-4 HERE \_\_\_\_\_

#### 42 43 44 **Box 4-4. Boreal – Tundra Biome Shift**

45  
46 Changes in a suite of ecological processes currently underway across the broader arctic region are consistent with  
47 earth system model predictions of climate-induced geographic shifts in the range extent and functioning of the  
48 tundra and boreal forest biomes (Figure 4-12). Thus far these changes appear to be not so much threshold responses  
49 as gradual and systematic shifts across temperature and moisture gradients. Responses are expressed through gross  
50 and net primary production, microbial respiration, fire and insect disturbance, vegetation composition, species range  
51 expansion and contraction, surface energy balance and hydrology, active layer depth and permafrost thaw, and a  
52 range of other inter-related variables. Because the high northern latitudes are warming more rapidly than other parts  
53 of the earth, due at least in part to arctic amplification (Serreze and Francis, 2006), the rate of change in these  
54 ecological processes are sufficiently rapid that they can be documented *in situ* (Hinzman *et al.*, 2005; Post *et al.*,

1 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).

3  
4 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.

15  
16 [INSERT FIGURE 4-12 HERE

17 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.]

24  
25 \_\_\_\_\_ END BOX 4-4 HERE \_\_\_\_\_

#### 26 27 28 4.3.3.5. *Highly Human-Modified Systems - Plantations, Bioenergy Systems,* 29 *Urban Ecosystems, Cultural Landscapes*

30  
31 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).

##### 34 35 36 4.3.3.5.1. *Plantation forestry*

37  
38 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).

46  
47 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).

1 Regarding future climatically driven changes, results from several studies with forest yield models suggest increases  
2 in forest production (Kirilenko and Sedjo, 2007), but these results may be overly optimistic because many models  
3 may overestimate potential positive effects of elevated CO<sub>2</sub> (Kirilenko and Sedjo, 2007; see 4.2.4.4) and the effects  
4 of disturbances, such as wildfires, forest pests, pathogens and windstorms, which are major drivers of forest  
5 dynamics, are often either poorly or not at all represented (Kirilenko and Sedjo, 2007). Using a model that accounts  
6 for fire effects and insect damage, Kurz *et al.* (2008), for example, showed that recent insect outbreaks might have  
7 caused a transition in the Canadian forest sector from a sink to a source of carbon. Future projections for particular  
8 stands or regions are also uncertain because results from different models often differ substantially, both regarding  
9 forest productivity (*e.g.* Sitch *et al.*, 2008; Keenan *et al.*, 2011) and potential species ranges (see 4.3.3.1.2).  
10 Nevertheless, decreased production is expected in particular in already dry forest regions for which further drying is  
11 projected, such as the south-western U.S. (Williams *et al.*, 2010a), and extreme drying might also decrease forest  
12 yields in currently not water-limited forests (*e.g.* Sitch *et al.*, 2008; see 4.3.3.1). Plantations in cold-limited areas  
13 could benefit from climate change and their productivity could increase if associated changes in disturbances, pests  
14 and pathogens do not outweigh the potential positive climatic effects.

15  
16 Many plantation forests are monospecies stands or sometimes even include only a limited number of clones of one  
17 species. In the temperate and boreal zone, native species are commonly used (but in some cases beyond their native  
18 range), while in the tropics, conventional tree planting is mainly based on exotic species from a few genera such as  
19 *Pinus*, *Eucalyptus* and *Acacia* grown in single-species stands. Low species (and often also genetic) diversity  
20 compared with natural stands might render plantation forests particularly vulnerable to climate change (*e.g.* Hemery,  
21 2008). Choosing provenances that are well adapted to current and future climates is extremely difficult because of  
22 uncertainties in climate projections (Broadmeadow *et al.*, 2005). Furthermore, it is highly uncertain how forest pests  
23 and pathogens will spread as a result of climate change and trade and new pathogen-tree interactions might occur  
24 (*e.g.* Brasier and Webber, 2010). Nevertheless, adaptive forest management can decrease the vulnerability of  
25 plantations to climate change (Hemery, 2008; Bolte *et al.*, 2009; Seppälä, 2009; Dale *et al.*, 2010). For example, risk  
26 spreading by promoting multi-species mixed stands and natural regeneration, which can increase genetic diversity  
27 (Kramer *et al.*, 2010), has been advocated as a plausible adaptation strategy for temperate forests (Hemery, 2008;  
28 Bolte *et al.*, 2010). Also in the tropics, recent approaches highlight the use of native species in mixed stands (Erskine  
29 *et al.*, 2006; Petit and Montagnini, 2006; Hall *et al.*, 2011), but missing information on the ecology of many of the  
30 tropical tree species and little experience in managing mixed tropical tree plantations remains to be a major problem  
31 (Hall *et al.*, 2011). At least at the southern border of cold-adapted species, such as Norway spruce (*Picea abies*) in  
32 Europe, climate change will *very likely* lead to a shift in the main tree species used for forest plantations (Iverson *et*  
33 *al.*, 2008; Bolte *et al.*, 2010).

#### 34 35 36 4.3.3.5.2. *Bioenergy systems*

37  
38 Bioenergy sources include traditional forms such as wood and charcoal and more modern forms such as the  
39 industrial burning of biomass wastes, the production of ethanol and biodiesel. While traditional biofuels have been  
40 in general decline as users switch to fossil fuels or electricity, they remain dominant energy sources in many less-  
41 developed parts of the world, such as Africa, and retain a niche in developed countries. The production of modern  
42 bioenergy is growing rapidly throughout the world in response to climate mitigation policies that incentivise their  
43 use, or as a strategy to decrease oil dependence and thus increase energy security (Cochrane and Barber, 2009). The  
44 WG III chapter on energy addresses their potential as a climate mitigation strategy, while the sensitivity of biofuel  
45 crops to climate change should be quite similar to those previously mentioned for plantation forestry (which to a  
46 large extent are grown for bioenergy purposes) and/or agricultural systems (WGII, chapter 7). In a review on climate  
47 change impacts on biofuel yields in temperate environments (Luckman and Kavanagh, 2000) it was concluded that  
48 elevated CO<sub>2</sub> might contribute to increase drought tolerance of bioenergy crops (as it is paralleled by improved plant  
49 water use), which may lead to constantly high yields. Generally, potentials of bioenergy production under climate  
50 change might be high, but are very uncertain (Ma and Zhou, 2012).

51  
52 An important part to deal with here is the ecosystem impacts of large-scale land-use changes related to the growing  
53 of bioenergy biofuels. Policy shifts in OECD countries favor the expansion of biofuel production, sometimes at the  
54 expense of food crop production, and placing new pressures on terrestrial and freshwater ecosystems (Searchinger *et*

1 *al.*, 2008; Lapola *et al.*, 2010). It is, for example, unclear if the global trend to reduced forest loss will continue -  
2 there are substantial pressures to deforest for the production of food and biofuels (Wise *et al.*, 2009; Meyfroidt and  
3 Lambin, 2011). Moiseyev *et al.*, (2011) found that in a 20 years perspective it is very little difference between the  
4 IPCC scenarios A1 and B2 regarding harvest level in Europe, and that the EU RES policy may only moderately  
5 influence the EU forestry and forest industries as long as the wood price paid by the bioenergy producers are below  
6 50-60 US\$ per m<sup>3</sup> wood. Under the assumption of doubling the growth rate of demand for bioenergy until 2030, a  
7 scenario by Martin *et al.* (2010) would lead to severe consequences for the global forest sector with a global  
8 reduction of forest stocks of 2 % or a 4% reduction for Asia.  
9

10 Bioenergy potentials are strongly influenced by human food requirements (incl. feed required for livestock), thus  
11 integrated approaches to optimize food and bioenergy are needed (Ma and Zhou, 2012). Such considerations ignore  
12 areas for the conservation of biodiversity and ecosystems. These are more explicitly dealt with by McAlpine *et al.*  
13 (2009) and Millar *et al.* (2004), while in both papers the usage of abandoned land, which was previously under  
14 agricultural use, is regarded as an option for biomass production which reduces net warming. However, this ignores  
15 for example that such habitats may be core elements in cultural landscapes of high conservation value (many species  
16 rich grasslands in Europe have been croplands before and later abandoned), and that the productivity of such areas  
17 could be too limited for biofuels (Mishra *et al.*, 2010). As an alternative, Fargione (2011) discusses biofuel crop  
18 yield increases on existing cropland, with the aim to avoid expansion of agriculture.  
19  
20

#### 21 4.3.3.5.3. *Cultural landscapes*

22

23 “Cultural landscapes are at the interface between nature and culture, tangible and intangible heritage, biological and  
24 cultural diversity—they represent a closely woven net of relationships, the essence of culture and people’s identity”  
25 (Rössler, 2006, p. 334). They are characterized by a long history of human-nature interactions, where man is the  
26 main driver and has often created open landscapes, rich in structures and often also in species. A UNESCO Flagship  
27 programme focusses especially on cultural landscapes (Rössler, 2006). These landscapes nowadays are often about  
28 to lose their roles as recreational species rich entities due to agricultural intensification and extensification  
29 (Huntington *et al.*, 2012). Well researched examples are grassland or mixed agriculture landscapes in Europe or rice  
30 landscapes in Asia (Kuldna *et al.*, 2009), while such landscapes may well exist across the globe (e.g., Rössler, 2006;  
31 Heckenberger *et al.*, 2007).  
32

33 In such landscapes, conservation efforts - as all across the globe - often focus on the conservation of ecosystems that  
34 contain endangered biotic communities. However, in such cultural landscapes this aim might be hard to achieve due  
35 to the very dynamic nature of systems. Keeping species in a favorable conservation status in cultural landscapes  
36 (one aim e.g. of European policies; EU Council, 1992), can normally only be achieved through appropriate  
37 management, as the vast majority of endangered species in the wider countryside depend on certain types of land use  
38 for their survival. This requires profound knowledge of the systems and species involved, and as this is rarely the  
39 case, conservation success was limited (see Kirdyanov *et al.*, 2012 for a notable exception).  
40

41 As in many other cases, population and niche models are available and partly already validated (Kirdyanov *et al.*,  
42 2012). This shows where future challenges are to be found: particularly in the quantification of relative importance  
43 of climate change in comparison with the habitat and its management (Settele and Kühn, 2009). So far the majority  
44 of changes can be attributed to land use as the most obvious driver (Nowicki *et al.*, 2007), while the impact of  
45 climate change can be readily detected in few examples (Devictor *et al.*, 2012), combined effects seem to better  
46 explain the overall picture (Schweiger *et al.*, 2008; Schweiger *et al.*, 2012), where attribution to climate change  
47 seems low to medium. As a consequence, it has been suggested to adjust the European Natura 2000 protected area  
48 network to take into account changing climatic conditions and to enable migration or dispersal of species across the  
49 landscape (Heubes *et al.*, 2011; Jin *et al.*, 2010).  
50  
51  
52

#### 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).

1  
2 Hole *et al.* (2009) report that the majority of African birds are projected to move large distances over the next 60  
3 years resulting in substantial turnover of species within protected areas (>50% turnover in more than 40% of  
4 Important Bird Areas of Africa) and migration across unfavorable habitats. Many birds may find suitable climate in  
5 the large network of protected areas, but will be forced to cope with new habitat constraints. Similarly, Araujo *et al.*,  
6 2011) indicate that approximately 60% of plants and vertebrate species would no longer have favorable climates  
7 within European protected areas, often pushing them into unsuitable or less preferred habitats. Wiens *et al.* (2011)  
8 project similar effects in the western US, but also find that climate change may open up new opportunities for  
9 protecting species in areas where climate is currently unsuitable. Indeed, in some changes climate change may allow  
10 some species to move into areas of lower current or future land use pressure including protected areas (Bomhard *et*  
11 *al.*, 2005). These and other studies strongly argue for a rethinking of protected areas networks and of the importance  
12 of the habitat matrix outside of protected areas as a key to migration and long-term survival of species.  
13

14 Over sufficiently long periods, biomes or habitat types may shift their distributions or disappear entirely due to  
15 climate change. Non-analog climates are projected to occur in the future (Williams *et al.*, 2007b; Wiens *et al.*,  
16 2011), and in the past climate shifts have resulted in vegetation types that have no current analog (section 4.2.2). The  
17 impacts of this on species abundance and extinction risk is difficult to evaluate because species may show  
18 substantial capacity to adapt to novel habitats (Prugh *et al.*, 2008; Willis and Bhagwat, 2009; Oliver *et al.*, 2009).  
19 This high uncertainty in habitat specificity for many species means it is not possible to predict if species extinctions  
20 due to climate induced loss of habitat will be below or far above current extinction rates caused by non-climate  
21 factors (Malcolm *et al.*, 2006). This does, however, also reinforce the idea that habitat quality across all components  
22 of landscapes will increase in importance for biodiversity conservation in the future.  
23  
24

25 Effects of climate change on habitat quality are less well studied than shifts in species or habitat distributions.  
26 However, several recent studies indicate that climate change may have and probably will alter habitat quality  
27 (Iverson *et al.*, 2011; Matthews *et al.*, 2011). For example, climate change induced changes in habitat quality due to  
28 decreasing snowfall may partially explain declining songbird populations in southwestern US (Martin and Maron,  
29 2012).  
30  
31

#### 32 4.3.4.2. *Pollination, Pest and Disease Regulation* 33

34 It can be inferred that global change will result in new communities (Schweiger *et al.*, 2010). As these will have  
35 experienced a much shorter (or even no) period of coevolution, drastic changes of ecological interactions like shifts  
36 in the use of certain plants by herbivores, in the range of prey of predators or in pollination networks are to be  
37 expected (Tylianakis *et al.*, 2008; Schweiger *et al.*, 2012). This might generally result in drastic changes in the  
38 provision of services (Montoya and Raffaelli, 2010).  
39

40 Among the regulating services most strongly related to biodiversity, pollination and biocontrol of pests have to be  
41 highlighted. Climate change tends to increase the abundance of pest species particularly in previously cooler  
42 climates, but assessments of changes in impacts are hard to make (Payette, 2007). Insect pests are directly  
43 influenced, e.g. through the quality of food plants (Payette and Fillion, 1985) or via the effects on their natural  
44 enemies (predators and parasitoids). Direct impacts are via the relatively high temperature optima of insects, which  
45 lead to increased vitality and reproduction (Allen *et al.*, 2010a). Mild winters in temperate areas promote frost  
46 susceptible pests. For the vast majority of indirect effects, e.g. spread of insect borne diseases, information is scarce  
47 (for further assessments on climate change effects on pest and disease dynamics see WGII, chapters 7 and 11).  
48

49 Climate change, after land-use changes, can be regarded as the second most relevant factor responsible for the  
50 decline of pollinators (Potts *et al.*, 2010; for other factors see Biesmeijer *et al.*, 2006; Brittain *et al.*, 2010a; Brittain  
51 *et al.*, 2010b). While the potential influence of climate change on pollination can be manifold (compare Hegland *et*  
52 *al.*, 2009; Roberts *et al.*, 2011; Schweiger *et al.*, 2010), there are only few observations which mostly relate to the  
53 de-coupling of plants and their pollinators – especially in relation to phenology (Gordo and Sanz, 2005). While  
54 Peñuelas and Boada (2003) states that these phenological effects may be less than feared, an analysis of

1 phonological observations in plants Wolkovich *et al.* (2012) shows that experimental data on phenology may grossly  
2 underestimate phenological shifts. As Willmer's (2003) view is partly based upon experimental observations, it has  
3 to be seen whether field evidence might proof something different (compare Phenology Chapter 4.3.2.1.).  
4

5 In relation to honeybees Le Conte and Navajas (2008) state that the generally observed decline is a clear indication  
6 for an increasing susceptibility against global change phenomena, with pesticide application, new diseases and stress  
7 (and a combination of these) as the most relevant causes. Climate change might contribute by modifying the balance  
8 between honeybees and their environment (incl. diseases). Honeybees also have shown a large capacity to adjust to a  
9 large variety of environments and their genetic variability should allow them to also cope with climatic change ,  
10 that's why the preservation of genetic variability within honeybees is regarded as a central aim to mitigate climate  
11 change impacts (Le Conte and Navajas, 2008).  
12  
13

#### 14 4.3.4.3. Climate Regulation Services

15  
16 Ecosystems moderate the local climate through a range of mechanisms, including reducing the near-ground wind  
17 velocity, cooling the air through shading and the evaporation of water and ameliorating low temperatures through  
18 releasing heat absorbed during the day or summer. This service is widely recognized and valued, for instance in the  
19 establishment of windbreaks, gardens and urban parks. The focus of this section is on processes operating at much  
20 larger scales – the region to the whole globe. Terrestrial ecosystems affect climate at large scales through their  
21 influence on the physical properties of the land surface and on the composition of the atmosphere with respect to  
22 radiatively-active gases and particles. In the decade 2000-2010, approximately one fourth of the CO<sub>2</sub> emitted to the  
23 atmosphere by human activities was taken up by terrestrial ecosystems, reducing the rate of climate change  
24 proportionately (4.3.2.3, WG 1 Chapter 6).  
25

26 One study (Arora and Montenegro, 2011) suggests that the overall effect of tropical afforestation on global  
27 temperature is up to 75% greater than would be expected on the basis of increased carbon storage alone, due to  
28 physical processes such as changes in evapotranspiration; but in other circumstances the cooling due to land-cover  
29 change may be *less* than that estimated from carbon uptake alone, due to decreased albedo (4.2.4.1). Observations  
30 and model evidence indicates that, broadly speaking, forests make warm areas cooler and cold areas warmer,  
31 through the competing effects of evapotranspiration (cooling) and surface albedo (in dark-canopied forests,  
32 generally warming). Model simulations suggest that if more than 40% of the pre-1700 extent of the Amazon forest  
33 were to be cleared, rainfall in the region would be reduced (Sampaio *et al.*, 2007). According to satellite  
34 observations, the effect of conversion of the Brazilian savannas (*cerrado*) to pasture is to induce a local warming,  
35 (Loarie *et al.*, 2011), which is partly offset when the pasture is converted to sugarcane. It has been suggested  
36 (Ridgwell *et al.*, 2009) that planting large areas of crop varieties with high-albedo leaves could help regional  
37 cooling. Model analysis indicates this strategy could be marginally effective at high latitudes, but have undesirable  
38 climate consequences at low latitudes, and measurements show that the current range of leaf albedo in major crops is  
39 insufficient to make a meaningful difference (Doughty *et al.*, 2011).  
40  
41

#### 42 4.3.4.4. Potable Water Supply

43  
44 Freshwater systems provide a range of ecosystem services that benefit society and are *likely* to be affected by  
45 climate change (see Table 4-1; Palmer and Filoso, 2009). Many of the implications of climate change on the  
46 provisioning services of water for food production and domestic supply are discussed in detail in WGII Chapter 3.  
47 Over 80% of the world's population is currently exposed to high levels of threat to water security because of land  
48 use change, pollution and water resource use (Vörösmarty *et al.*, 2010). Under climate change, reliability of surface  
49 water supply is *likely* to decrease due to increased temporal variations of river flow that are caused by increased  
50 variability in precipitation and decreased snow/ice storage (see WGII Chapter 3). In some Mediterranean regions,  
51 e.g. the southwest of Western Australia, significant reductions in surface flows have already forced governments to  
52 pursue alternative water sources (desalination, recycled wastewater) (see  
53 <http://www.watercorporation.com.au/watersupply/index.html>). In snow dominated regions, warming will mean that  
54 less winter precipitation falls as snow and melting of winter snow occurs earlier in spring (*high confidence*; Barnett

1 *et al.*, 2005). This means a shift in peak discharge to winter and early spring and away from summer and autumn  
2 when human demand is highest. In some locations, water storages may not be sufficient to capture winter runoff,  
3 particularly if they are also used to safeguard downstream communities from flooding (Barnett *et al.*, 2005). Climate  
4 change not only poses risks to the quantity of water available for human society but also the quality. Warming will  
5 exacerbate many of the symptoms of eutrophication, including the increased frequency and intensity of harmful  
6 cyanobacterial blooms (Paerl and Paul, 2012). Reduced summer flows in rivers increases residence time for algal  
7 growth, increases the risk of low dissolved oxygen events and associated poor water quality, and limits the ability to  
8 dilute pollution from point sources (Jeppesen *et al.*, 2010).

#### 11 **4.4. Adaptation and its Limits**

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

##### 22 **4.4.1. Autonomous Adaptation by Ecosystems and Wild Organisms**

24 Autonomous adaptation (see glossary) refers to the adjustments made by ecosystems, including their human  
25 components, without external intervention, in response to a changing environment (Smit *et al.*, 2000); also called  
26 ‘spontaneous adaptation’ (Smit *et al.*, 2007). In the context of human systems it is sometimes referred to as ‘coping  
27 capacity’. The capacity for autonomous adaptation is necessary for resilience but is not synonymous with that term  
28 as it is now used (Walker *et al.*, 2004). Here we focus on adaptation to a changing climate in all its manifestations,  
29 recognizing that climate change in the narrow sense is necessarily associated with changing CO<sub>2</sub> and ozone, and in  
30 practice is usually accompanied by changing land use, abundance of competing or mutualistic organisms and other  
31 environmental stressors, such as pollution.

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

##### 47 **4.4.1.1. Phenological and Physiological**

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



1  
2 Phenology is typically highly adapted to the climate seasonality of the environment in which the organism evolved.  
3 The phenology of any species also needs to be keyed to the phenology of other species with which it interacts, such  
4 as competitors, food species and pollinators. Thus change in phenology is a sensitive indicator of adaptation  
5 (Menzel *et al.*, 2006), but also a potential mechanism of ecosystem disruption if adaptation is insufficiently rapid or  
6 coordinated between interdependent species, or is cued to environmental signals that are not affected by climate  
7 change, such as day-length (Bradley *et al.*, 1999; Both and Visser, 2001; Parmesan, 2006). The environmental cues  
8 for phenological events are complex and multi-layered (Körner and Basler, 2010; Singer and Parmesan, 2010). For  
9 instance, late-succession temperate trees require a chilling period in winter, followed by a threshold in daylength,  
10 and only then are sensitive to temperature. As a result, projecting current phenological trends forward is risky, since  
11 the relative importance of cues can change (Cook *et al.*, 2012). The effects are complex and sometimes apparently  
12 counterintuitive, such as the increased sensitivity of flowering in high-altitude perennial herbs in the Rocky  
13 mountains to frost as a result of earlier snowmelt (Inouye, 2008).  
14

15 The importance of adaptation and potential for disruption from different rates of phenological change are illustrated  
16 by the consequences of timing of migratory bird activities (see 4.3.2.1.). Breeding is most effective when  
17 synchronized with the availability of food, so changes in the phenology of food supplies can exert a selective  
18 pressure on birds. In a study of 100 European migratory bird species, those that advanced their arrival showed stable  
19 or increasing populations, while that did not adjust their arrival date on average showed declining populations  
20 (Møller *et al.*, 2008). In a comparison of nine Dutch populations of the migratory pied flycatcher (*Ficedula*  
21 *hypoleuca*) over two decades, populations declined by 90% in areas where food peaked early in the season and the  
22 arrival of the birds was mis-timed, unlike areas with a later food peak which can still be exploited by early-breeding  
23 birds (Both *et al.*, 2006). Selection for earlier laying dates has been shown to stronger in warmer years when food  
24 supply (caterpillars) peaked early (Coppack and Both, 2002). Systematic cross-taxa studies in the USA and UK  
25 indicate different rates of phenological change for different species and trophic levels (Parmesan, 2007; Cook *et al.*,  
26 2008; Thackeray *et al.*, 2010).  
27

28 It has been suggested that shorter generation times would give greater opportunity for autonomous adaptation  
29 through natural selection (Rosenheim and Tabashnik, 1991; Bertaux *et al.*, 2004), but a standardized assessment of  
30 25,532 rates of phenological change for 726 UK taxa indicated that generation time only had limited influence  
31 (Thackeray *et al.*, 2010).  
32

33 The physiological processes in organisms can either adapt through plasticity or genetically (i.e., through evolution).  
34 The former is generally regarded as rapid but limited, and the latter as less constrained, but slow (see 4.4.1.2)  
35 although long-term studies of a few organisms indicate rapid genetic adaptation to a changing climate (Bradshaw  
36 and Holzapfel, 2006). Acclimation to higher temperatures and/or higher CO<sub>2</sub> concentrations is seen in many  
37 organisms, but to very widely varying extents and general understanding remains limited (Hofmann and Todgham,  
38 2010). A physiological process with large potential consequences for the global carbon cycle and thus the climate  
39 system is the sensitivity of the relationship between organism temperature and respiration rate, particularly in  
40 decomposer organisms (Jones *et al.*, 2003). The shape of the relationship varies between locations with different  
41 climates and shows apparent acclimation within months or years to a changing climate (Giardina and Ryan, 2000;  
42 Luo *et al.*, 2001; Rustad, 2001). The relationship is also dependent on C substrate type and the presence of other  
43 respiration-controlling environmental factors, complicating the determination of the inherent rate and its adaptation  
44 to a changing climate. Several competing hypotheses can explain the observed reduction in respiration rates in soil  
45 warming experiments after an initial peak – physiological adaptation; depletion of readily available substrate  
46 (Kirschbaum, 2004); and varying temperature sensitivities in different soil carbon pools (Knorr *et al.*, 2005).  
47

#### 48 4.4.1.2. Evolutionary and Genetic

49 Since the AR4 report there has been substantial progress in defining the concepts and tools necessary for  
50 documenting and predicting evolutionary and genetic responses to recent and future climate change, often referred  
51 to as "rapid evolution". Evolution can occur through many mechanisms including selection of existing resistant  
52 genes or genotypes within populations, hybridization, mutation and selection of new adaptive genes and perhaps  
53  
54

1 even through epigenetics (Chevin *et al.*, 2010; Chown *et al.*, 2010; (Lavergne *et al.*, 2010; Paun *et al.*, 2010;  
2 Hoffmann and Sgro, 2011; Anderson *et al.*, 2012b; Donnelly *et al.*, 2012; Franks and Hoffmann, 2012; Hegarty,  
3 2012; Merilä, 2012; Bell, 2013; Zhang *et al.*, 2013). Mechanisms such as selection of existing genes and genotypes,  
4 hybridization and epigenetics can lead to adaptation in very few generations, while others, notably mutation and  
5 selection of new genes, typically take at least many tens of generations. This means that species with very fast life  
6 cycles, e.g., bacteria, should in general have greater capacity to respond to climate change than species with long life  
7 cycles such as large mammals and trees. Unfortunately, there remains a paucity of observational or experimental  
8 data that can be used for detection and attribution of climate signals and for validation of models and theory.  
9

10 *Observed Evolutionary and Genetic Responses to Rapid Changes in Climate* - There is a small, but growing body of  
11 observational evidence supporting studies reviewed in the AR4 report that some species have adapted to recent  
12 climate warming or to climatic extremes through genetic responses (e.g., plants - Franks and Weis, 2008; Anderson  
13 *et al.*, 2012a; Hill *et al.*, 2011; vertebrates - Ozgul *et al.*, 2010; Husby *et al.*, 2011; Phillimore *et al.* (2010; Karell  
14 *et al.*, 2011; insects - Buckley *et al.*, 2012; van Asch *et al.*, 2012). For example, Karell *et al.* (2011) found increasing  
15 numbers of brown genotypes of the tawny owl in Finland over the course of the last 28 years and attributed it to  
16 fewer snow-rich winters, which creates strong selection pressure against the heritable white genotype. Phillimore  
17 *et al.* (2010) showed for the common frog in Britain, that population differences in earlier spawning due to increasing  
18 spring temperatures could be attributed largely to local genetic adaptation. Using a combination of models and  
19 observations Visser and colleagues have built a case for detection and attribution of genetic adaptation in an  
20 insectivorous bird (Husby *et al.*, 2011), and in a herbivorous insect that has tracked warming related changes in the  
21 budburst timing of its host tree (van Asch *et al.*, 2012). In contrast, many species appear to be maladapted to  
22 changing climates or to respond to recent warming through phenotypic plasticity, in part because factors such as  
23 limited standing genetic variation, weak heritability of adaptive traits or conflicting constraints on adaptation create  
24 low potential for rapid evolution (Knudsen *et al.*, 2011; Ketola *et al.*, 2012; Mihoub *et al.*, 2012; Merilä, 2012).  
25 Most studies of rapid evolution suffer from methodological weakness making it difficult to clearly demonstrate a  
26 genetic basis underlying observed phenotypic responses to environmental change (Gienapp *et al.*, 2008; Franks and  
27 Hoffmann, 2012; Hansen *et al.*, 2012; Merilä, 2012). When combined with recent progress on conceptual  
28 frameworks, rapid advances in quantitative genetics, genomics and phylogenetics will substantially improve the  
29 detection and attribution of genetic responses to changing climate over the next few years (Davis *et al.*, 2010;  
30 Salamin *et al.*, 2010; Hoffmann and Sgro, 2011).  
31

32 The ability of species to adapt to new environmental conditions through rapid evolutionary processes can also be  
33 inferred from the degree to which environmental niches are conserved when environment is changed. There is good  
34 evidence that environmental niches are conserved for some species under some conditions (plants - Petitpierre *et al.*  
35 (2012; birds - Monahan and Tingley, 2012; review - Peterson *et al.*, 2011), but also evidence suggesting that  
36 environmental niches can evolve over time scales of several decades following invasion or changes in climate  
37 (Broennimann *et al.*, 2007; Angetter *et al.*, 2011; Konarzewski *et al.*, 2012; Leal and Gunderson, 2012; Lavergne  
38 *et al.*, 2013). The paleontological record also provides insight into past evolutionary response in the face of natural  
39 climate variation. In general, environmental niches appear to be broadly conserved through time although there is  
40 insufficient data to determine the extent to which genetic adaptation has attenuated range shifts and changes in  
41 population size (Peterson *et al.*, 2011; Willis and MacDonald, 2011). Phylogeographic reconstructions of past  
42 species distributions suggest that hybridization may have helped avoid extinctions during cycles of glaciation and  
43 could also play a key role in future adaptation (Soliani *et al.*, 2012; Hegarty, 2012). There is also new evidence that  
44 epigenetic mechanisms, such as DNA methylation, can play a role in heritable and potentially very rapid adaptation  
45 to climate (Paun *et al.*, 2010; Zhang *et al.*, 2013), but understanding of these mechanisms is too preliminary to know  
46 how important they are for adaptation to climate change.  
47

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

1 at range boundaries (Bell and Gonzalez, 2009). Generalization will be complicated by the interactions between local  
2 adaptation, gene flow and population dynamics (Bridle *et al.*, 2010).

3  
4 Substantial progress has been made since the AR4 report in developing models that can be used to explore whether  
5 genetic adaptation will be fast enough to track climate change. Models of long-lived tree species suggest that  
6 existing genetic variation may be sufficient to significantly attenuate negative impacts of future climate change  
7 (Kuparinen *et al.*, 2010; Kremer *et al.*, 2012), which is coherent with observations and experiments (Jump *et al.*,  
8 2006, Jump *et al.*, 2008). However, these studies also indicate that adaptive responses will lag far behind even  
9 modest rates of projected rates of climate change, in large part due to the very long generation time of trees. In a  
10 species with much shorter generation times, the great tit (*Parus major*), Gienapp *et al.* (2013) found that modeled  
11 breeding times tracked climate change, but only at low to moderate rates of change. For a species with an even faster  
12 life cycle, van Asch *et al.*, (2007, 2012) predicted that rapid evolution of the phenological response of a herbivorous  
13 insect should have allowed it to track recent warming, which it has. This suggests substantial capacity for future  
14 adaptation in this insect since current and moderate future rates of future climate change are similar. Kearney *et al.*  
15 (2009) on the other hand found that rapid evolutionary responses only modestly affected modeled range shifts in a  
16 mosquito species in response to climate change. More broadly, Walters *et al.* (2012) found that modeled extinction  
17 risk in ectotherms - species that do not internally regulate their body temperature - is substantially reduced by genetic  
18 adaptation at rates of climate change that are roughly less than 0.02°C per generation. Based on these assumptions,  
19 species with short generation times such as most insects potentially have the capacity to genetically adapt to even  
20 the most rapid rates of projected climate change (Figure 4-6), but species with longer generation times could be at  
21 risk of extinction at moderate to high rates of climate change. Recent experimental work on "evolutionary rescue"  
22 shows that long-term avoidance of extinction through genetic adaptation to hostile environments can occur under  
23 certain conditions (Bell, 2013). Generalizations coming from experiments and theoretical work are that evolutionary  
24 rescue requires large initial genetic variation and population sizes and is accompanied by substantial loss of genetic  
25 diversity, reductions in population size and range contractions over many generations before population recovery  
26 (Bell, 2013; Schiffers *et al.*, 2013). Model-based projections must, however, be viewed with considerable caution  
27 because there are many evolutionary and ecological mechanisms that can either speed up or inhibit heritable  
28 adaptation to climate change that are not accounted for in most models (Cobben *et al.*, 2012; Norberg *et al.*, 2012;  
29 Kovach-Orr and Fussmann, 2013). In some cases, accounting for evolutionary processes in models even leads to  
30 predictions of enhanced maladaptation to climate change and more rapid population declines under certain  
31 conditions (Ferriere and Legendre, 2013). Phenotypic plasticity is thought to generally improve the odds of  
32 adaptation to climate change, but the extent to which it contributes to adaptive capacity depends a great deal on the  
33 costs of plasticity in terms of fitness (Chevin *et al.*, 2010). High plasticity in the face of climate change that has low  
34 costs can greatly improve the odds of adapting to climate change; however, plasticity that has high fitness costs can  
35 have much more modest effects on the odds of adaptation.

36  
37 The AR4 report concluded that "projected rates of climate change are *very likely* to exceed rates of evolutionary  
38 adaptation in many species (*high confidence*". Work since then provides a similar, but more nuanced view of rapid  
39 evolution in the face of climate change. There are few observational studies of rapid evolution and difficulties in  
40 detection and attribution, so there is only *medium confidence* that some species have responded to recent changes in  
41 climate through genetic adaptations, and insufficient evidence to determine if this is a widespread phenomenon (thus  
42 *low confidence* across all species). The lack of adaptation in some species to recent changes in climate, broad  
43 support for niche conservatism and models showing limited adaptive capacity especially in species with long  
44 generation times, all indicate that high rates of climate change (RCP8.5) will exceed the adaptive capacities of many  
45 species (*high confidence*). On the other hand, evidence from observations and models also indicates that there is  
46 substantial capacity for genetic adaptation to attenuate phenological shifts, population declines and local extinctions  
47 in many species, especially for low rates of climate change (RCP2.6) (*high confidence*). Projected adaptation to  
48 climate change is frequently characterized by population declines and loss of genetic diversity for many generations  
49 (*medium confidence*), thereby increasing species vulnerability to other pressures and potentially impacting  
50 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 maladaptation (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 21<sup>st</sup> 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

1 independently (Heller and Zavaleta, 2009); since it is the network of habitats and protected areas that confers  
2 resilience rather than any single element; and better integration of protected areas with a biodiversity-hospitable  
3 landscape outside is more effective than treating the protected areas as islands (Willis and Bhagwat, 2009).

#### 6 4.4.2.3. *Landscape and Watershed Management*

7  
8 The general principles for management adaptations in United States were summarized from a major literature review  
9 by West *et al.*, 2009. They suggest that in the context of climate change a successful management of natural  
10 resources will require cycling between ‘managing for resilience’ and ‘managing for change’. This requires the  
11 anticipation of changes that can alter the impacts of grazing, fire, logging, harvesting, recreation, and so on. At the  
12 national level, the necessary changes in practice to facilitate adaptation include: (1) management at appropriate  
13 scales, and not necessarily the scales of convenience or tradition; (2) increased collaboration among agencies; (3)  
14 rational approaches for establishing priorities and applying triage; and (4) management with the expectation of  
15 ecosystem change, rather than keeping them as they have been. Barriers and opportunities were divided into four  
16 categories: (1) legislation and regulations, (2) management policies and procedures, (3) human and financial capital,  
17 and (4) information and science.

18  
19 In 14,000 ha of forested watersheds in central Nova Scotia, Canada, the adaptation to climate change was assessed  
20 using the landscape disturbance model LANDIS-II, (Steenberg *et al.*, 2011). The study simulated the impact of three  
21 components of timber harvesting: the canopy-opening size of harvests, the age of harvested trees within a stand, and  
22 the species composition of harvested trees within a stand. The combination of all three adaptation treatments  
23 allowed target species and old forest to remain reasonably well represented without diminishing the timber supply.  
24 This minimized the trade-offs between management values and climate adaptation objectives.

#### 27 4.4.2.4. *Assisted Migration*

28  
29 Assisted migration has been proposed when fragmentation of habitats limits migration potential or when natural  
30 migration rates are outstripped by the pace of climate change, (Hoegh-Guldberg *et al.*, 2008; Vitt *et al.*, 2010;  
31 Chmura *et al.*, 2011; Loss *et al.*, 2011). The options for management can be summarized as: i) try to maintain or  
32 improve existing habitat so that species don't have to move, ii) maintain or improve migration corridors, including  
33 active management to improve survival along the moving margin of the distribution (Lawson *et al.*, 2012), or iii)  
34 intervene heavily by translocating species (Hoegh-Guldberg *et al.*, 2008; Loss *et al.*, 2011). There is *low agreement*  
35 in the scientific community whether it is best to increase the resilience of ecosystems to climate change, thus help to  
36 preserve existing communities, or to enhance the capacity of ecosystems to transform in the face of the  
37 overwhelming forces of species migration and modifications of ecosystem function by climate change.

38  
39 There is *high agreement* among the scientific and conservation community that maintaining or improving migration  
40 corridors or ecological networks is a low-regret strategy, partly because it is also seen as useful in combatting the  
41 negative effects of habitat fragmentation on population dynamics (Hole *et al.*, 2011; Jongman *et al.*, 2011). This  
42 approach has the benefit of improving the migration potential for large numbers of species and is therefore a more  
43 ecosystemic approach than assisted migration for individual species. However, observational and modeling studies  
44 show that increases in habitat connectivity do not always improve the population dynamics of target species, may  
45 decrease species diversity, and may also facilitate the spread of invasive species (Cadotte, 2006; Brisson *et al.*, 2010;  
46 Matthiessen *et al.*, 2010).

47  
48 There is *medium agreement* that the practice of assisted migration of targeted species is a useful adaptation option  
49 (Hoegh-Guldberg *et al.*, 2008; Loss *et al.*, 2011; Vitt *et al.*, 2009; Willis and Bhagwat, 2009; Hewitt *et al.*, 2011).  
50 The speed of 21st century climate change and substantial habitat fragmentation in many areas of the world mean that  
51 many species will be unable to migrate or adapt fast enough to keep pace with climate change. If this results in  
52 significant reductions in range size it will pose problems for long-term survival of the species. Some ecologists  
53 believe that careful selection of species to be moved would minimize the risk of undesirable impacts on existing  
54 communities or ecosystem function (Minteer and Collins, 2010), but others argue that the history of intentional

1 species introductions shows that the outcomes are unpredictable and in many cases have had disastrous impacts  
2 (Ricciardi and Simberloff, 2009). The number of species that could potentially require assisted migration that could  
3 easily overwhelm funding capacity (Minteer and Collins, 2010). The degree and magnitude of phenotypic responses  
4 or genetic adaptation to climate change are very variable among species, making decisions regarding which species  
5 should be translocated complex and debatable.

#### 6 7 8 *4.4.2.5. Ex Situ Conservation* 9

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

19  
20 Several issues remain largely unresolved (Li and Pritchard, 2009). The physiological, institutional and economic  
21 sustainability of such efforts into the indefinite future is unclear. The fraction of the intra-specific variation that  
22 needs to be preserved for future viability and how much genetic bias is introduced by founder effects and selection  
23 pressures applied during ex-situ maintenance is unknown. It remains uncertain whether it is possible to reintroduce  
24 species (especially animals) successfully into the wild after generations of ex-situ conservation.

#### 25 26 27 *4.4.3. Consequences and Costs of Inaction and Benefits of Action* 28

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

39  
40 A comprehensive cost estimate of the effects of climate change on ecosystem service provision is not available. ten  
41 Brink *et al.* (2008) report the monetary cost of not meeting the 2010 biodiversity goals in terms of lost value of  
42 ecosystem services. Their model incorporates climate change, among other pressures, and concludes that cumulative  
43 losses of welfare due to losses in ecosystem service provision could reach an annual amount of 14 trillion Euro  
44 (based on values of 2007), in 2050 equivalent to 7% of projected global GDP for that year.

45  
46 Economic calculations are appropriate when at least one component of the ecosystem services is traded in markets  
47 (such as for biofuels; Mishra *et al.*, 2010). If climate regulation services are translated into a tradable item, through  
48 carbon markets or payments for avoiding deforestation, then their value can be expressed via market prices (Shaw *et*  
49 *al.*, 2011).

50  
51 The market price for carbon is volatile, linked to speculation and political agreements on emission reduction. There  
52 is a range of estimates from \$23/metric ton of carbon to \$371, in current 1995 and 2007 dollars respectively (Tol,  
53 2008; Watkiss and Downing, 2008). In the South-African Fynbos region, economic viability of afforestation proved  
54 to be highly sensitive to the value of carbon (Chisholm, 2010). The realized prices of the traded carbon have been on

1 average lower than the figures mentioned above. The proposed global REDD programs, financed by carbon-offset  
2 trading, rely on the premises on which market-based payment for ecosystem services (PES) are founded. However, a  
3 decade of PES experience demonstrates a clash between market-efficiency criteria and poverty reduction and  
4 therefore a risk of regressive wealth redistribution (McAfee, 2012).

5  
6 Uncertainty about the potential consequences of abrupt changes advises against valuation of ecosystems close to  
7 critical thresholds (TEEB, 2009). Similar difficulties can be argued in the presence of irreversible changes, as in the  
8 case of irreversible biodiversity losses or damage to cultural services such as World Heritage sites (Viles and Cutler,  
9 2012).

#### 10 11 12 **4.4.4. Unintended Consequences of Adaptation and Mitigation Actions in This and Other Sectors**

13  
14 Some issues relevant to this section are also found in 4.2.2 and in Chapter 14.

15  
16 Several of the alternatives to fossil fuel require extensive use of the land surface. Bio-energy requires land to either  
17 be taken from food production or from natural ecosystems. Many renewables require significant land areas.  
18 Hydroelectricity usually involves the impoundment of large bodies of water behind dams, leading to flooding of pre-  
19 existing ecosystems. Solar energy effectively involves decreasing the albedo of areas of ground surface. Large-scale  
20 wind energy involves the location of arrays of turbines across the landscape. As an illustration, the “aggressive  
21 mitigation” scenario RPC2.6 relies heavily on both bio-energy and renewables as major components of the energy  
22 mix (van Vuuren *et al.*, 2011), so there is clear potential for unintended consequences for terrestrial and inland water  
23 systems.

24  
25 In RCP2.6, although food production remains dominant, the scenario still involves some land use / land-cover  
26 change (Box 4-1) in order to facilitate the use of bio-energy. By 2100, bio-energy crops occupy approximately 4  
27 million km<sup>2</sup>, approximately 7% of global cultivated land projected at the time. Modification of the landscape and the  
28 fragmentation of habitats are major influences on extinction risk (Fischer and Lindenmayer, 2007), especially if  
29 native vegetation cover is reduced or degraded, human land use is intensive and “natural” areas become  
30 disconnected. Hence, additional extensification of cultivated areas for energy crops may pose extinction risks.

31  
32 RCP2.6 also includes a substantial increase in renewables above current levels of deployment, either as hydropower,  
33 solar or wind. Damming of river systems for hydropower can cause fragmentation of the inland water habitat with  
34 implications for fish species, and monitoring studies indicate that flooding of ecosystems behind the dams can lead  
35 to declining populations, e.g., of amphibians (Brandão and Araújo, 2007). Large dams may also result in CH<sub>4</sub>  
36 emissions due to decay of flooded vegetation in anaerobic conditions and the subsequent release of CH<sub>4</sub> from the  
37 water surface and especially from water passing through turbines and spillways (Fearnside, 2005; Lima *et al.*, 2008),  
38 so dams may act as sources of greenhouse gas emissions.

39  
40 Concern is often raised over wind turbines posing a danger to birds and bats, but estimating mortality rates is  
41 complex and difficult (Smallwood, 2007). It has been estimated that wind farms in Europe and the USA cause  
42 between 0.3 and 0.4 wildlife fatalities per gigawatt-hour (GWh) of electricity, and while nuclear and fossil-fuel  
43 power stations are estimated to cause approximately 5.2 fatalities per GWh (Sovacool, 2009), although this  
44 quantification has been criticized as having key methodological flaws (Willis *et al.*, 2010b). One study found on-site  
45 bird populations to be generally affected more by windfarm construction than subsequent operation, with some  
46 populations recovering after construction (Pearce-Higgins *et al.*, 2012)

47  
48 Solar energy systems, by design, aim to maximize the absorption of solar energy and hence widespread deployment  
49 of photovoltaics (PV) has the potential to exert a positive radiative forcing on climate through decreased surface  
50 albedo. In a scenario of widespread deployment of solar PV, such a forcing is estimated to be 30 times smaller than  
51 the avoided radiative forcing arising from the use of PV to substitute fossil fuels, so overall PV still exerts a net  
52 reduction of climate warming (Nemet, 2009). Nevertheless, at the local scale there are some plausible circumstances  
53 in which the decreased surface albedo substantially reduces the effectiveness of PV as a negative climate forcing  
54 (Nemet, 2009).

1  
2 Adaption measures may also result in unintended consequences. Relocation of agricultural areas as a climate change  
3 adaptation measure could pose risks of habitat fragmentation and loss similar to those discussed above in the context  
4 of mitigation through bio-energy. Deliberate relocation of vulnerable and important species – assisted migration –  
5 may also be a potential conservation measure in the context of facilitating adaptation to climate change (Maclachlan  
6 *et al.*, 2007). However this may directly conflict with other conservation priorities, for example by actually  
7 facilitating the introduction of invasive species (Maclachlan *et al.*, 2007).  
8

9 Proactive adaptation measures may also have unforeseen consequences politically. Carey *et al.* (2011) argue that  
10 improved water management in a glacial lake in the Peruvian Andes in 1985 led to increased tensions over many  
11 years and ultimately local civil action against the authorities in 2008. Introduction of a tunnel to reduce the risk of a  
12 glacial lake outburst flood facilitated proactive human management of the lake levels, but in the context of changes  
13 in the wider political situation, power struggles arose between different stakeholders due to different and conflicting  
14 interests. This may provide an example of how attempts by society to exert more direct control over the environment  
15 can lead to unintended impacts.  
16  
17

#### 18 **4.5. Emerging Issues and Key Uncertainties** 19

20 The presence of thresholds in ecosystem response to climate change, and specifically the type of thresholds  
21 characterized as “tipping points”, is a growing concern but remains a major source of uncertainty. In general (Field  
22 *et al.*, 2007), negative feedbacks currently dominate the climate-ecosystem interaction, but in several areas, such as  
23 the boreal ecosystems, positive feedbacks could dominate, even under moderate warming. For most ecological  
24 processes, increasing magnitude of warming shifts the balance towards positive rather than negative feedbacks  
25 (Field *et al.*, 2007). For positive feedbacks to propagate into ‘runaway’ processes leading to a new ecosystem state,  
26 the strength of the feedback has to exceed that of the initial perturbation. This has not as yet been demonstrated for  
27 any large-scale, plausible and immanent ecological process; but the risk is non-negligible and the consequences if it  
28 did occur would be severe: thus further research is needed. The issue of biophysical feedbacks between ecosystem  
29 state and the climate, over and above the effects mediated through greenhouse gases, is emerging as significant in  
30 many areas. Such effects include those caused by changes in surface reflectivity (albedo) or the partitioning of  
31 energy between latent energy and sensible heat.  
32

33 Uncertainty in predicting the response of ecosystems to climate and other perturbations remains a major impediment  
34 to determining prudent levels of permissible change. A significant source of this uncertainty stems from the inherent  
35 complexity of ecosystems, especially where they are coupled to equally-complex social systems. The high number  
36 of interactions can lead to cascading effects (Biggs *et al.*, 2011). Some of this uncertainty can be removed by  
37 understanding the systems better, but some will remain irreducible because of the failure of predictive models when  
38 faced with mathematical bifurcations – a problem that is well-known in climate science. Probabilistic statements  
39 about the range of outcomes are possible in this context, but ecosystem science is mostly as yet unable to conduct  
40 such analyses routinely and rigorously. One consequence is the ongoing difficulty in attributing observed changes  
41 unequivocally to climate change. More comprehensive monitoring is a key element of the solution.  
42

43 Studies of the combined effects of multiple simultaneous elements of global change, such as the effects of elevated  
44 carbon dioxide and rising tropospheric ozone on plant productivity - which has critical consequences for the future  
45 sink strength of the biosphere, since they of similar magnitude but opposite sign – are needed as a supplement to the  
46 single-factor experiments.  
47

48 Understanding of the tolerable *rate* of climate change is as important as understanding the tolerable *magnitude*.  
49 Despite being explicitly required under Article 2 of the UNFCCC, rate studies are currently less developed and more  
50 uncertain than magnitude (equilibrium) studies. This includes evidence for the achievable migration rates of a range  
51 of species as well as the rate of micro-evolutionary change.  
52

53 The costs of assisted adaptation ecosystems, biodiversity and ecosystem services to a changing climates is poorly  
54 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<sub>2</sub> 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<sub>2</sub> 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 EUR 153 billion per year (a value that nearly doubles if you take into account purchasing power parity of the affected countries)

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

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

8  
9 **FAQ 4.6: Can land-use and land-cover changes cause changes in climate?**

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

16  
17 **FAQ 4.7: Will the number of alien species increase due to climate change?**

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

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

36  
37  
38 **Cross-Chapter Boxes**

39  
40 **Box CC-EA. Ecosystem Based Approaches to Adaptation - Emerging Opportunities**

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

42  
43 Ecosystem-based approaches to adaptation (also termed Ecosystem-based Adaptation, EBA) integrate the use of  
44 biodiversity and ecosystem services into climate change adaptation strategies (e.g., CBD, 2009; Munroe *et al.*, 2011;  
45 Munroe *et al.*, 2011). EBA is implemented through the sustainable management of natural resources, as well as  
46 conservation and restoration of ecosystems, to provide and sustain services that facilitate adaptation both to climate  
47 variability and change (Colls *et al.*, 2009). The CBD COP 10 Decision X/33 on Climate Change and Biodiversity  
48 states further that effective EBA also “takes into account the multiple social, economic and cultural co-benefits for  
49 local communities”.

50  
51 The potential for EBA is increasingly being realized (e.g., Munroe *et al.*, 2011), offering opportunities that integrate  
52 with or even substitute for the use of engineered infrastructure or other technological approaches. Engineered  
53 defenses such as dams, sea walls and levees, may adversely affect biodiversity, resulting in maladaptation due to  
54 damage to ecosystem regulating services (Campbell *et al.*, 2009, Munroe *et al.*, 2011). There is some evidence that

1 the restoration and use of ecosystem services may reduce or delay the need for these engineering solutions (CBD,  
2 2009). Well-integrated EBA is also more cost effective and sustainable than non-integrated physical engineering  
3 approaches, and may contribute to achieving sustainable development goals (e.g., poverty reduction, sustainable  
4 environmental management, and even mitigation objectives), especially when they are integrated with sound  
5 ecosystem management approaches. EBA also offers lower risk of maladaptation than engineering solutions in that  
6 their application is more flexible and responsive to unanticipated environmental changes.

7  
8 EBA provides opportunities particularly in developing countries where economies depend more directly on the  
9 provision of ecosystem services (Vignola *et al.*, 2009), to reduce risks to climate change impacts and ensure that  
10 development proceeds on a pathways that are resilient to climate change (Munang *et al.*, ). In these settings,  
11 ecosystem-based adaptation projects may be readily developed by enhancing existing initiatives, such as  
12 community-based adaptation and natural resource management approaches (e.g., Khan *et al.*, 2012, Midgley *et al.*,  
13 2012; Roberts *et al.*, 2012)

14  
15 Examples of ecosystem based approaches to adaptation include:

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

29  
30 It is important to assess the appropriate and effective application of EBA as a developing concept through learning  
31 from work underway, and to build understanding of the social and physical conditions that may limit its  
32 effectiveness. Application of EBA, like other approaches, is not without risk, and risk/benefit assessments will allow  
33 better assessment of opportunities offered by the approach.

34  
35 [INSERT FIGURE EA-1 HERE

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

#### 41 42 43 CC-EA References

- 44  
45 **Campbell**, A., Kapos, V., Scharlemann, J., Bubb, P., Chenery, A., Coad, L., Dickson, B., Doswald, N., Khan, M., Kershaw, F., and Rashid, M.,  
46 2009: *Review of the Literature on the Links between Biodiversity and Climate Change: Impacts, Adaptation and Mitigation. Technical*  
47 *Series No. 42.* Montreal, Canada, 124pp. pp.
- 48 **CBD**, 2009: *Ad Hoc Technical Expert Group: Climate Change and Biodiversity.* Montreal, Canada, pp.
- 49 **Colls**, A., Ash, N., and Ikkala, N., 2009: *Ecosystem-based Adaptation: a natural response to climate change.* Gland, Switzerland, 16pp pp.
- 50 **Khan**, A.S., Ramachandran, A., Usha, N., Punitha, S., and Selvam, V., 2012: Predicted impact of the sea-level rise at Vellar-Coleroon estuarine  
51 region of Tamil Nadu coast in India: Mainstreaming adaptation as a coastal zone management option. *Ocean & Coastal Management*, **69**,  
52 327-339.
- 53 **Midgley**, G.S.M., Barnett, M., and Wågsæther, K., 2012: *Biodiversity, climate change and sustainable development – Harnessing synergies and*  
54 *celebrating successes. Final Technical Report.* pp.

- 1 **Munang, R., Thiaw, I., Alverson, K., Mumba, M., Liu, J., and Rivington, M., 2013:** Climate change and Ecosystem-based Adaptation: a new  
2 pragmatic approach to buffering climate change impacts. *Current Opinion in Environmental Sustainability*.
- 3 **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*  
4 *effectiveness of ecosystem-based approaches to adaptation*. Nairobi, Kenya, pp.
- 5 **Opperman, J.J., Galloway, G.E., Fargione, J., Mount, J.F., Richter, B.D., and Secchi, S., 2009:** Sustainable floodplains through large-scale  
6 reconnection to rivers. *Science*, **326(5959)**, 1487-1488.
- 7 **Roberts, D., Boon, R., Diederichs, N., Douwes, E., Govender, N., McInnes, A., McLean, C., O'Donoghue, S., and Spiers, M., 2012:** Exploring  
8 ecosystem-based adaptation in Durban, South Africa: "learning-by-doing" at the local government coal face. *Environment and*  
9 *Urbanization*, **24(1)**, 167-195.
- 10 **Vignola, R., Locatelli, B., Martinez, C., and Imbach, P., 2009:** Ecosystem-based adaptation to climate change: what role for policymakers,  
11 society and scientists? *Mitigation and Adaptation Strategies for Global Change*, **14(8)**, 691-696.

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

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

16  
17 It is widely acknowledged that the flow regime is a primary determinant of the structure and function of rivers and their  
18 associated floodplain wetlands, and flow alteration is considered to be a serious and continuing threat to freshwater  
19 ecosystems (Bunn and Arthington, 2002; Poff and Zimmerman, 2010; Poff *et al.*, 2010). Most species distribution  
20 models do not consider the effect of changing flow regimes (i.e. changes to the frequency, magnitude, duration  
21 and/or timing of key flow parameters) or they use precipitation as proxy for river flow (Heino *et al.*, 2009).

22  
23 There is growing evidence that climate change will significantly alter ecologically important attributes of hydrologic  
24 regimes in rivers and wetlands, and exacerbate impacts from human water use in developed river basins (Aldous *et*  
25 *al.*, 2011; Xenopoulos *et al.*, 2005). By the 2050s, climate change is projected to impact river flow characteristics  
26 like long-term average discharge, seasonality and statistical high flows (but not statistical low flows) more strongly  
27 than dam construction and water withdrawals have done up to the year 2000 (Figure RF-1; Döll and Zhang, 2010).  
28 For one climate scenario, 15% of the global land area may suffer, by the 2050s, from a decrease of fish species in  
29 the upstream basin of more than 10%, as compared to only 10% of the land area that has already suffered from such  
30 decreases due to water withdrawals and dams (Döll and Zhang, 2010). Climate change may exacerbate the negative  
31 impacts of dams for freshwater ecosystems but may also provide opportunities for operating dams and power  
32 stations to the benefit of riverine ecosystems. This is the case if total runoff increases and, like in Sweden, the annual  
33 hydrograph becomes more similar to variation in electricity demand, i.e. with a lower spring flood and increased  
34 run-off during winter months (Renofalt *et al.*, 2010).

35  
36 [INSERT FIGURE RF-1 HERE

37 Figure RF-1: Impact of climate change on the ecologically relevant river flow characteristics mean annual river flow  
38 and monthly low flow  $Q_{90}$  as compared to the impact of water withdrawals and dams on natural flows, as computed  
39 by a global water model (Döll and Zhang, 2010). Impact of climate change is the percent change of flow between  
40 1961-1990 and 2041-2070 according to the emissions scenario A2 as implemented by the global climate model  
41 HadCM3. Impact of water withdrawals and reservoirs is computed by running the model with and without water  
42 withdrawals and dams that existed in 2002.]

43  
44 Because biota are often adapted to a certain level of river flow variability, the larger variability of river flows that is  
45 due to increased climate variability is *likely* to select for generalist or invasive species (Ficke *et al.*, 2007). The  
46 relatively stable habitats of groundwater-fed streams in snow-dominated or glacierized basins may be altered by  
47 reduced recharge by meltwater and as a result experience more variable (possibly intermittent) flows (Hannah *et al.*,  
48 2007). A high-impact change of flow variability is a flow regime shift from intermittent to perennial or vice versa. It  
49 is projected that until the 2050s, river flow regime shifts may occur on 5-7% of the global land area, mainly in semi-  
50 arid areas (Döll and Müller Schmied, 2012; see Chapter 3, Table 3-2).

51  
52 In Africa, one third of fish species and one fifth of the endemic fish species occur in eco-regions that may  
53 experience a change in discharge or runoff of more than 40% by the 2050s (Thieme *et al.*, 2010). Eco-regions  
54 containing over 80% of Africa's freshwater fish species and several outstanding ecological and evolutionary

1 phenomena are *likely* to experience hydrologic conditions substantially different from the present, with alterations in  
2 long-term average annual river discharge or runoff of more than 10% due to climate change and water use (Thieme  
3 *et al.*, 2010).  
4

5 Due to increased winter temperatures, freshwater ecosystems in basins with significant snow storage are affected by  
6 higher river flows in winter, earlier spring peak flows and possibly reduced summer low flows (chapter 3.2.3).  
7 Strongly increased winter peak flows may lead to a decline in salmonid populations in the Pacific Northwest of the  
8 USA of 20-40% by the 2050s (depending on the climate model) due to scouring of the streambed during egg  
9 incubation, the relatively pristine high-elevation areas being affected most (Battin *et al.*, 2007). Reductions in  
10 summer low flows will increase the competition for water between ecosystems and irrigation water users (Stewart *et al.*,  
11 2005). Ensuring environmental flows through purchasing or leasing water rights and altering reservoir release  
12 patterns will be an important adaptation strategy (Palmer *et al.*, 2009).  
13

14 Observations and models suggest that global warming impacts on glacier and snow-fed streams and rivers will pass  
15 through two contrasting phases (Burkett *et al.*, 2005; Vuille *et al.*, 2008; Jacobsen *et al.*, 2012). In the first phase,  
16 when river discharge is increased due to intensified melting, the overall diversity and abundance of species may  
17 increase. However, changes in water temperature and stream-flow may have negative impacts on narrow range  
18 endemics (Jacobsen *et al.*, 2012). In the second phase, when snowfields melt early and glaciers have shrunk to the  
19 point that late-summer stream flow is reduced, broad negative impacts are foreseen, with species diversity rapidly  
20 declining once a critical threshold of roughly 50% glacial cover is crossed (Figure RF-2).  
21

22 [INSERT FIGURE RF-2 HERE

23 Figure RF-2: Accumulated loss of regional species richness (gamma diversity) as a function of glacial cover GCC.  
24 Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment  
25 drops below approximately 50%. Each data point represents a river site and lines are Lowess fits. Adapted by  
26 permission from Macmillan Publishers Ltd: *Nature Climate Change*, Jacobsen *et al.*, 2012, © 2012.]  
27

28 River discharge also influences the response of river temperatures to increases of air temperature. Globally  
29 averaged, air temperature increases of 2°C, 4°C and 6°C are estimated to lead to increases of annual mean river  
30 temperatures of 1.3°C, 2.6°C and 3.8°, respectively (van Vliet *et al.*, 2011). Discharge decreases of 20% and 40%  
31 are computed to result in additional increases of river water temperature of 0.3° C and 0.8°C on average (van Vliet  
32 *et al.*, 2011). Therefore, where rivers will experience drought more frequently in the future, freshwater-dependent  
33 biota will suffer not only directly by changed flow conditions but also by drought-induced river temperature  
34 increases, as well as by related decreased oxygen and increased pollutant concentrations.  
35

### 36 CC-RF References

- 37  
38  
39 **Aldous**, A., Fitzsimons, J., Richter, B., and Bach, L., 2011: Droughts, floods and freshwater ecosystems: evaluating climate change impacts and  
40 developing adaptation strategies. *Marine and Freshwater Research*, **62(3)**, 223-231.  
41 **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  
42 salmon habitat restoration. *Proceedings of the National Academy of Sciences*, **104(16)**, 6720-6725.  
43 **Bunn**, S.E., and Arthington, A.H., 2002: Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity.  
44 *Environmental Management*, **30(4)**, 492-507.  
45 **Burkett**, V.R., Wilcox, D.A., Stottlemeyer, R., Barrow, W., Fagre, D., Baron, J., Price, J., Nielsen, J.L., Allen, C.D., Peterson, D.L., Ruggerone,  
46 G., and Doyle, T., 2005: Nonlinear dynamics in ecosystem response to climatic change: Case studies and policy implications. *Ecological*  
47 *Complexity*, **2(4)**, 357-394.  
48 **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?  
49 A global-scale analysis. *Environmental Research Letters*, **7(1)**.  
50 **Döll**, P., and Zhang, J., 2010: Impact of climate change on freshwater ecosystems: a global-scale analysis of ecologically relevant river flow  
51 alterations. *Hydrology and Earth System Sciences*, **14(5)**, 783-799.  
52 **Ficke**, A.D., Myrick, C.A., and Hansen, L.J., 2007: Potential impacts of global climate change on freshwater fisheries. *Reviews in Fish Biology*  
53 *and Fisheries*, **17(4)**, 581-613.

- 1 **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  
2 climate-hydrology-ecology for alpine river systems. *Aquatic Conservation-Marine and Freshwater Ecosystems*, **17(6)**, 636-656.
- 3 **Heino, J.,** Virkkala, R., and Toivonen, H., 2009: Climate change and freshwater biodiversity: detected patterns, future trends and adaptations in  
4 northern regions. *Biological Reviews*, **84(1)**, 39-54.
- 5 **Jacobsen, D.,** Milner, A.M., Brown, L.E., and Dangles, O., 2012: Biodiversity under threat in glacier-fed river systems. *Nature Clim. Change*,  
6 **2(5)**, 361-364.
- 7 **Palmer, M.A.,** Lettenmaier, D.P., Poff, N.L., Postel, S.L., Richter, B., and Warner, R., 2009: Climate change and river ecosystems: protection  
8 and adaptation options. *Environmental Management*, **44**, 1053-1068.
- 9 **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.,  
10 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:  
11 The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards.  
12 *Freshwater Biology*, **55(1)**, 147-170.
- 13 **Poff, N.L.,** and Zimmerman, J.K.H., 2010: Ecological responses to altered flow regimes: a literature review to inform the science and  
14 management of environmental flows. *Freshwater Biology*, **55**, 194-205.
- 15 **Renofalt, B.M.,** Jansson, R., and Nilsson, C., 2010: Effects of hydropower generation and opportunities for environmental flow management in  
16 Swedish riverine ecosystems. *Freshwater Biology*, **55(1)**, 49-67.
- 17 **Stewart, I.T.,** Cayan, D.R., and Dettinger, M.D., 2005: Changes toward earlier streamflow timing across western North America. *Journal of*  
18 *Climate*, **18(8)**, 1136-1155.
- 19 **Thieme, M.L.,** Lehner, B., Abell, R., and Matthews, J., 2010: Exposure of Africa's freshwater biodiversity to a changing climate. *Conservation*  
20 *Letters*, **3(5)**, 324-331.
- 21 **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  
22 warming and changes in river flow. *Water Resources Research*, **47(W02544)**, 1-19.
- 23 **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,  
24 present and future. *Earth-Science Reviews*, **89(3-4)**, 79-96.
- 25 **Xenopoulos, M.A.,** Lodge, D.M., Alcamo, J., Marker, M., Schulze, K., and Van Vuuren, D.P., 2005: Scenarios of freshwater fish extinctions  
26 from climate change and water withdrawal. *Global Change Biology*, **11(10)**, 1557-1564.

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

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

31  
32 Terrestrial vegetation dynamics, carbon and water cycles are closely coupled, for example by the simultaneous  
33 transpiration and CO<sub>2</sub> uptake through plant stomata in the process of photosynthesis, and by feedbacks of land cover  
34 and land use change on water cycling. Numerous experimental studies have demonstrated that elevated atmospheric  
35 CO<sub>2</sub> concentration leads to reduced opening of stomatal apertures, associated with a decrease in leaf-level  
36 transpiration (de Boer *et al.*, 2011; Reddy *et al.*, 2011). This physiological effect of CO<sub>2</sub> is associated with an  
37 increased intrinsic water use efficiency (iWUE) of plants, as less water is transpired per unit of carbon assimilated.  
38 Records of stable carbon isotopes in woody plants (Peñuelas *et al.*, 2011) corroborate this finding, suggesting an  
39 increase in iWUE of mature trees by 20.5% between the 1970s and 2000s. Increases since pre-industrial times have  
40 also been found for several forest sites (Andreu-Hayles *et al.*, 2011; Gagen *et al.*, 2011; Loader *et al.*, 2011; Nock *et*  
41 *al.*, 2011) and in a temperate semi-natural grassland (Koehler *et al.*, 2010), although in one boreal tree species iWUE  
42 ceased to increase after 1970 (Gagen *et al.*, 2011). However, the physiological CO<sub>2</sub> effect is accompanied by  
43 structural changes to C3 plants (including all tree species), i.e. increased biomass production, spatial encroachment  
44 and, thus, higher transpiration, as confirmed by Free Air CO<sub>2</sub> Enrichment (FACE) techniques (Leakey *et al.*, 2009).

45  
46 There are conflicting views on whether the direct CO<sub>2</sub> effects on plants already have a significant influence on  
47 evapotranspiration and runoff at global scale. AR4 reported work by Gedney *et al.*, (2006) which suggested that  
48 physiological CO<sub>2</sub> effects (lower transpiration) contributed to a supposed global increase in runoff seen in  
49 reconstructions by (Labat *et al.*, 2004). However, a more recent dataset (Dai *et al.*, 2009) showed different runoff  
50 trends in some areas. Detection of ecosystem influences on terrestrial water flows, hence, critically depends on the  
51 availability and quality of hydrometeorological observations (Haddeland *et al.*, 2011; Lorenz and Kunstmann,  
52 2012).

53  
54 A key influence on the significance of increased iWUE for large-scale transpiration is whether overall leaf area of

1 primary vegetation has remained approximately constant (Gedney *et al.*, 2006) or has increased in some regions due  
2 to structural CO<sub>2</sub> effects (as assumed in models by Piao *et al.*, 2007; Gerten *et al.*, 2008). While field-based results  
3 vary considerably between sites, tree ring studies suggest that tree growth did not increase globally since the 1970s  
4 in response to climate and CO<sub>2</sub> change (Peñuelas *et al.*, 2011; Andreu-Hayles *et al.*, 2011). However, basal area  
5 measurements at over 200 plots across the tropics suggest that biomass and growth rates in intact tropical forests  
6 have increased in recent decades (Lewis *et al.*, 2009), which is also confirmed for 55 temperate forest plots, with a  
7 suspected contribution of CO<sub>2</sub> rise (McMahon *et al.*, 2010). The net impact of CO<sub>2</sub> on global-scale transpiration and  
8 runoff therefore remains poorly constrained.  
9

10 Moreover, model results differ in terms of the importance of CO<sub>2</sub> effects for historical runoff relative to other drivers  
11 such as climate, land use change and irrigation water withdrawal. Other than Gedney *et al.*, (2006), Piao *et al.*,  
12 (2007) and Gerten *et al.*, (2008) found that CO<sub>2</sub> effects on global runoff were small relative to effects of  
13 precipitation, and that land use change (which often acts to decrease evapotranspiration and to increase runoff) was  
14 of second-most importance, as also supported by Sterling *et al.*, (2012) data and model analysis. By contrast, using a  
15 shorter time period and a smaller selection of river basins, Alkama *et al.*, 2011(2011) suggested that global effects of  
16 land use change on runoff have been negligible. Oliveira *et al.*, 2011(2011) furthermore point to the importance of  
17 changes in incident solar radiation and the mediating role of vegetation; their global simulations demonstrate, for  
18 example, that a higher diffuse radiation fraction during 1960–1990 increased evapotranspiration in the tropics by 3%  
19 due to increased photosynthesis from shaded leaves. Since the anthropogenic component of the precipitation and  
20 temperature contributions (i.e. of the radiative CO<sub>2</sub> effect) to runoff trends is not yet established, a full attribution of  
21 anthropogenic emissions of CO<sub>2</sub> (and other greenhouse gases) is still missing.  
22

23 Analogously, there is uncertainty about how vegetation responses to future increases in CO<sub>2</sub> will modulate effects of  
24 climate change on the terrestrial water balance. 21<sup>st</sup>-century continental- and basin-scale runoff is projected by some  
25 models to either increase more or decrease less when CO<sub>2</sub>-induced increases in iWUE are included in addition to  
26 climate change (Betts *et al.*, 2007; Murray *et al.*, 2012), potentially reducing an increase in water stress due to rising  
27 population or climate change (Wiltshire *et al.*, submitted) – although other models project a smaller response (Cao *et al.*,  
28 2009). Direct effects of CO<sub>2</sub> on plants have been modelled to increase future global runoff by 4–5% (Gerten *et al.*,  
29 2008) up to 13% (Nugent and Matthews, 2012), depending on the assumed CO<sub>2</sub> trajectory and whether  
30 feedbacks of changes in vegetation structure and distribution to the climate are accounted for. The model analysis by  
31 Alkama *et al.*, (2010) suggests that although the physiological CO<sub>2</sub> effect will be the second-most important factor  
32 for 21<sup>st</sup>-century global runoff and although both physiological and structural effects will amplify compared to historic  
33 conditions, runoff changes will still primarily follow the projected climatic changes. Using a large ensemble of  
34 climate change projections, Konzmann *et al.*, (2013) put hydrological changes into an agricultural perspective and  
35 suggest that direct CO<sub>2</sub> effects on crops reduce their irrigation requirements (Fig. CC-VW-1). Thus, adverse climate  
36 change impacts on crop yields might be partly buffered as iWUE improves (Fader *et al.*, 2010), but only if proper  
37 management abates limitation of plant growth by nutrient availability or other factors. Lower transpiration under  
38 rising CO<sub>2</sub> may also affect future regional climate change itself (Boucher *et al.*, 2009) and may enhance the contrast  
39 between land and ocean surface warming (Joshi *et al.*, 2008).  
40

41 Application of a soil-vegetation-atmosphere-transfer model indicates complex responses of groundwater recharge to  
42 changes in different climatic variables mediated by vegetation, with computed groundwater recharge being always  
43 larger than would be expected from just accounting for changes in rainfall (McCallum *et al.*, 2010). In a warmer  
44 climate with increased atmospheric CO<sub>2</sub> concentration, iWUE of plants increases and leaf area may either increase  
45 or decrease, and even though precipitation may slightly decrease, groundwater recharge may increase as a net effect  
46 of these interactions (Crosbie *et al.*, 2010). Depending on the type of grass in Australia, the same change in climate  
47 is suggested to lead to either increasing or decreasing groundwater recharge in this location (Green *et al.*, 2007). For  
48 a location in the Netherlands, a biomass decrease was computed for each of eight climate scenarios indicating drier  
49 summers and wetter winters (A2 emissions scenario), using a fully coupled vegetation and variably saturated  
50 hydrological model. The resulting increase in groundwater recharge up-slope was simulated to lead to higher water  
51 tables and an extended habitat for down-slope moisture-adapted vegetation (Brolsma *et al.*, 2010).  
52

53 Future anthropogenic and climate-driven land cover and land use changes will also affect regional  
54 evapotranspiration, surface and subsurface water flows, with the direction and magnitude of these changes

1 depending on the direction and intensity of the changes in vegetation coverage, as shown e.g. for a river basin in  
 2 Iowa (Schilling *et al.*, 2008) or for the Elbe river basin (Conradt *et al.*, 2012). Removal of vegetation acting as source  
 3 of atmospheric moisture can change regional water cycling and decrease potential crop yields by up to 17% in  
 4 regions otherwise receiving this moisture in the form of precipitation (Bagley *et al.*, 2012). Changes in vegetation  
 5 coverage and structure due to long-term climate change or shorter-term extreme events such as droughts (Anderegg  
 6 *et al.*, 2013) also affect the partitioning of precipitation into evapotranspiration and runoff, sometimes involving  
 7 complex feedbacks with the climate system such as in the Amazon region (Port *et al.*, 2012; Saatchi *et al.*, 2013). As  
 8 water, carbon and vegetation dynamics evolve synchronously and interactively under climate change (Heyder *et al.*,  
 9 2011) in that e.g. vegetation structure and composition can dynamically adapt to changing climatic and hydrologic  
 10 conditions (Gerten *et al.*, 2007), it remains a challenge to disentangle the effects of future land cover changes on the  
 11 water cycle.

12  
 13 [INSERT FIGURE VW-1 HERE

14 Figure VW-1: Percentage change (ensemble median across 19 GCMs used to force a vegetation and hydrology  
 15 model) in net irrigation requirements of 12 major crops by the 2080s, assuming current extent of irrigation areas and  
 16 current management practices. Top: impacts of climate change only; bottom: additionally considering physiological  
 17 and structural crop responses to increased atmospheric CO<sub>2</sub> concentration. Taken from Konzmann *et al.* (2013).]  
 18  
 19

#### 20 CC-VW References

- 21  
 22 **Alkama, R., Decharme, B., Douville, H., and Ribes, A., 2011:** Trends in Global and Basin-Scale Runoff over the Late Twentieth Century:  
 23 Methodological Issues and Sources of Uncertainty. *Journal of Climate*, **24(12)**, 3000-3014.  
 24 **Alkama, R., Kageyama, M., and Ramstein, G., 2010:** Relative contributions of climate change, stomatal closure, and leaf area index changes to  
 25 20th and 21st century runoff change: A modelling approach using the Organizing Carbon and Hydrology in Dynamic Ecosystems  
 26 (ORCHIDEE) land surface model. *Journal of Geophysical Research: Atmospheres*, **115(D17)**, n/a-n/a.  
 27 **Anderegg, W.R.L., Kane, J.M., and Anderegg, L.D.L., 2013:** Consequences of widespread tree mortality triggered by drought and temperature  
 28 stress. *Nature Climate Change*, **3(1)**, 30-36.  
 29 **Andreu-Hayles, L., Planells, O., Guti rrez, E., Muntan, E., Helle, G., Anchukaitis, K.J., and Schleser, G.H., 2011:** Long tree-ring chronologies  
 30 reveal 20th century increases in water-use efficiency but no enhancement of tree growth at five Iberian pine forests. *Global Change*  
 31 *Biology*, **17(6)**, 2095-2112.  
 32 **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  
 33 the world's breadbaskets. *Environmental Research Letters*, **7(1)**, 014009.  
 34 **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**  
 35 **Webb, M.J., 2007:** Projected increase in continental runoff due to plant responses to increasing carbon dioxide. *Nature*, **448(7157)**, 1037-  
 36 1041.  
 37 **Boucher, O., Jones, A., and Betts, R.A., 2009:** Climate response to the physiological impact of carbon dioxide on plants in the Met Office  
 38 Unified Model HadCM3. *Climate Dynamics*, **32(2-3)**, 237-249.  
 39 **Brolsma, R.J., van Vliet, M.T.H., and Bierkens, M.F.P., 2010:** Climate change impact on a groundwater-influenced hillslope ecosystem. *Water*  
 40 *Resources Research*, **46(11)**, n/a-n/a.  
 41 **Cao, L., Bala, G., Caldeira, K., Nemani, R., and Ban-Weiss, G., 2009:** Climate response to physiological forcing of carbon dioxide simulated by  
 42 the coupled Community Atmosphere Model (CAM3.1) and Community Land Model (CLM3.0). *Geophysical Research Letters*, **36(10)**, n/a-  
 43 n/a.  
 44 **Conradt, T., Koch, H., Hattermann, F., and Wechsung, F., 2012:** Spatially differentiated management-revised discharge scenarios for an  
 45 integrated analysis of multi-realisation climate and land use scenarios for the Elbe River basin. *Regional Environmental Change*, **12(3)**,  
 46 633-648.  
 47 **Crosbie, R., McCallum, J., Walker, G., and Chiew, F.S., 2010:** Modelling climate-change impacts on groundwater recharge in the Murray-  
 48 Darling Basin, Australia. *Hydrogeology Journal*, **18(7)**, 1639-1656.  
 49 **Dai, A., Qian, T., Trenberth, K.E., and Milliman, J.D., 2009:** Changes in Continental Freshwater Discharge from 1948 to 2004. *Journal of*  
 50 *Climate*, **22(10)**, 2773-2792.  
 51 **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  
 52 of maximal leaf conductance in subtropical vegetation under rising CO<sub>2</sub>. *Proceedings of the National Academy of Sciences*, **108(10)**, 4041-  
 53 4046.



- 1 **Fader, M., Rost, S., Müller, C., Bondeau, A., and Gerten, D., 2010:** Virtual water content of temperate cereals and maize: Present and potential  
2 future patterns. *Journal of Hydrology*, **384(3–4)**, 218-231.
- 3 **Gagen, M., Finsinger, W., Wagner-Cremer, F., McCarroll, D., Loader, N.J., Robertson, I., Jalkanen, R., Young, G., and Kirchhefer, A., 2011:**  
4 Evidence of changing intrinsic water-use efficiency under rising atmospheric CO<sub>2</sub> concentrations in Boreal Fennoscandia from subfossil  
5 leaves and tree ring  $\delta^{13}\text{C}$  ratios. *Global Change Biology*, **17(2)**, 1064-1072.
- 6 **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  
7 continental river runoff records. *Nature*, **439(7078)**, 835-838.
- 8 **Gerten, D., Rost, S., von Bloh, W., and Lucht, W., 2008:** Causes of change in 20th century global river discharge. *Geophysical Research Letters*,  
9 **35(20)**, n/a-n/a.
- 10 **Gerten, D., Schaphoff, S., and Lucht, W., 2007:** Potential future changes in water limitations of the terrestrial biosphere. *Climatic Change*, **80(3-**  
11 **4)**, 277-299.
- 12 **Green, T.R., Bates, B.C., Charles, S.P., and Fleming, P.M., 2007:** Physically Based Simulation of Potential Effects of Carbon Dioxide–Altered  
13 Climates on Groundwater Recharge All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any  
14 means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in  
15 writing from the publisher. *Vadose Zone J.*, **6(3)**, 597-609.
- 16 **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,  
17 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.,  
18 and Yeh, P., 2011:** Multimodel Estimate of the Global Terrestrial Water Balance: Setup and First Results. *Journal of Hydrometeorology*,  
19 **12(5)**, 869-884.
- 20 **Heyder, U., Schaphoff, S., Gerten, D., and Lucht, W., 2011:** Risk of severe climate change impact on the terrestrial biosphere. *Environmental*  
21 *Research Letters*, **6(3)**, 034036.
- 22 **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  
23 simulations of climate change. *Climate Dynamics*, **30(5)**, 455-465.
- 24 **Koehler, I.H., Poulton, P.R., Auerwald, K., and Schnyder, H., 2010:** Intrinsic water-use efficiency of temperate seminatural grassland has  
25 increased since 1857: an analysis of carbon isotope discrimination of herbage from the Park Grass Experiment. *Global Change Biology*,  
26 **16(5)**, 1531-1541.
- 27 **Konzmann, M., Gerten, D., and Heinke, J., 2013:** Climate impacts on global irrigation requirements under 19 GCMs, simulated with a  
28 vegetation and hydrology model. *Hydrological Sciences Journal*, **58(1)**, 88-105.
- 29 **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**,  
30 631-642.
- 31 **Leakey, A.D.B., Ainsworth, E.A., Bernacchi, C.J., Rogers, A., Long, S.P., and Ort, D.R., 2009:** Elevated CO<sub>2</sub> effects on plant carbon, nitrogen,  
32 and water relations: six important lessons from FACE. *Journal of Experimental Botany*, **60(10)**, 2859-2876.
- 33 **Lewis, S.L., Lloyd, J., Sitch, S., Mitchard, E.T.A., and Laurance, W.F., 2009:** Changing Ecology of Tropical Forests: Evidence and Drivers.  
34 *Annual Review of Ecology Evolution and Systematics*, **40**, 529-549.
- 35 **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  
36 trends in the intrinsic water-use efficiency of ringless rainforest trees in Borneo. *Philosophical Transactions of the Royal Society B:*  
37 *Biological Sciences*, **366(1582)**, 3330-3339.
- 38 **Lorenz, C., and Kunstmann, H., 2012:** The Hydrological Cycle in Three State-of-the-Art Reanalyses: Intercomparison and Performance  
39 Analysis. *Journal of Hydrometeorology*, **13(5)**, 1397-1420.
- 40 **McCallum, J.L., Crosbie, R.S., Walker, G.R., and Dawes, W.R., 2010:** Impacts of climate change on groundwater in Australia: a sensitivity  
41 analysis of recharge. *Hydrogeology Journal*, **18(7)**, 1625-1638.
- 42 **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*  
43 *Sciences*, **107(8)**, 3611-3615.
- 44 **Murray, S.J., Foster, P.N., and Prentice, I.C., 2012:** Future global water resources with respect to climate change and water withdrawals as  
45 estimated by a dynamic global vegetation model. *Journal of Hydrology*, **448–449(0)**, 14-29.
- 46 **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  
47 efficiency do not lead to increased stem growth in a tropical monsoon forest in western Thailand. *Global Change Biology*, **17(2)**, 1049-  
48 1063.
- 49 **Nugent, K.A., and Matthews, H.D., 2012:** Drivers of Future Northern Latitude Runoff Change. *Atmosphere-Ocean*, **50(2)**, 197-206.
- 50 **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:  
51 a global sensitivity study. *Global Change Biology*, **17(11)**, 3453-3467.
- 52 **Peñuelas, J., Canadell, J.G., and Ogaya, R., 2011:** Increased water-use efficiency during the 20th century did not translate into enhanced tree  
53 growth. *Global Ecology and Biogeography*, **20(4)**, 597-608.

- 1 **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  
2 direct impact than rising CO<sub>2</sub> on global river runoff trends. *Proceedings of the National Academy of Sciences*, **104(39)**, 15242-15247.
- 3 **Port, U., Brovkin, V., and Claussen, M., 2012:** The influence of vegetation dynamics on anthropogenic climate change. *Earth Syst. Dynam.*, **3(2)**,  
4 233-243.
- 5 **Reddy, A.R., Rasineni, G.K., and Raghavendra, A.S., 2011:** The impact of global elevated CO<sub>2</sub> concentration on photosynthesis and plant  
6 productivity. *Current Science*, **99**, 46-57.
- 7 **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  
8 severe drought on Amazonian forest canopy. *Proceedings of the National Academy of Sciences*, **110(2)**, 565-570.
- 9 **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  
10 of a large agricultural watershed: Historical effects and future directions. *Water Resources Research*, **44(7)**, n/a-n/a.
- 11 **Sterling, S.M., Ducharne, A., and Polcher, J., 2012:** The impact of global land-cover change on the terrestrial water cycle. *Nature Clim. Change*,  
12 **advance online publication.**
- 13 **Wiltshire, A., Betts, R., Booth, B., Dennis, E., Falloon, P., Gornall, J., and McNeall, D., submitted:** The relative importance of population,  
14 climate change and CO<sub>2</sub> plant physiological forcing in determining future global water stress. *Global Environmental Change*.

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

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

20  
21 Water, energy, and food are linked through numerous interactive pathways and subject to a changing climate, as  
22 depicted in Figure CC-WE-1. The depth and intensity of those linkages vary enormously between regions and  
23 production systems. Some energy technologies (biofuels, hydropower, thermal power plants), transportation fuels  
24 and modes and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops)  
25 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,  
26 Cary and Weber 2008). In irrigated agriculture, climate, crop choice and yields determine water requirements per  
27 unit of produced crop, and in areas where water must be pumped or treated, energy must be provided (Kahn and  
28 Hajra 2009, Gerten et al. 2011). While food production and transport require large amounts of energy (Pelletier et al  
29 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food  
30 production for land and water (7.3.2, Diffenbaugh et al 2012, Skaggs et al, 2012).

31  
32 [INSERT FIGURE WE-1 HERE

33 Figure WE-1: The water-energy-food nexus as related to climate change.]

34  
35 Most energy production methods require significant amounts of water, either directly (e.g. crop-based energy  
36 sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (Chapter 10.2.2  
37 and 10.3.4, and Davies et al 2013, van Vliet et al 2012). Water is also required for mining, processing, and residue  
38 disposal of fossil fuels. Water for biofuels, for example, has been reported by Gerbens-Leenes et al. 2012 who  
39 computed a scenario of water use for biofuels for transport in 2030 based on the Alternative Policy Scenario of the  
40 IEA. Under this scenario, global consumptive irrigation water use for biofuel production is projected to increase  
41 from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on  
42 freshwater resources, with potential negative impacts on freshwater ecosystems. Water for energy currently ranges  
43 from a few percent to more than 50% of freshwater withdrawals, depending on the region and future water  
44 requirements will depend on electric demand growth, the portfolio of generation technologies and water  
45 management options employed (WEC 2010, Sattler et al., 2012). Future water availability for energy production will  
46 change due to climate change (Chapter 3.5.2.2).

47  
48 Water may require significant amounts of energy for lifting, transport and distribution, treatment or desalination.  
49 Non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per  
50 m<sup>3</sup> of water vary by about a factor of 10 between different sources, e.g. locally produced or reclaimed wastewater  
51 vs. desalinated seawater (Plappally and Lienhard 2012, Macknick et al, 2012b). Groundwater (35% of total global  
52 water withdrawals, with irrigated food production being the largest user, Döll et al. 2012) is generally more energy  
53 intensive than surface water – in some countries, 40% of total energy use is for pumping groundwater. Pumping  
54 from greater depth (following falling groundwater tables) increases energy demand significantly– electricity use

1 (kWhr/m<sup>3</sup>) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard 2012). A lack of  
2 water security can lead to increasing energy demand and vice versa, e.g. over-irrigation in response to electricity or  
3 water supply gaps.

4  
5 Other linkages through land use and management, e.g. afforestation, can affect water as well as other ecosystem  
6 services, climate and water cycles (4.4.4, Box 25-10). Land degradation often reduces efficiency of water and  
7 energy use (e.g. resulting in higher fertilizer demand and surface runoff), and many of these interactions can  
8 compromise food security (3.7.2, 4.4.4). Only a few reports have begun to evaluate the multiple interactions among  
9 energy, food, land, and water (McCornick *et al.*, 2008, Bazilian *et al.*, 2011, Bierbaum and Matson, 2013),  
10 addressing the issues from a security standpoint and describing early integrated modeling approaches. The  
11 interaction among each of these factors is influenced by the changing climate, which in turn impacts energy demand,  
12 bioproductivity and other factors (see Figure WE-1 and Wise et al, 2009), and has implications for security of  
13 supplies of energy, food and water, adaptation and mitigation pathways, air pollution reduction as well as the  
14 implications for health and economic impacts as described throughout this Assessment Report.

#### 15 16 17 CC-WE References

- 18  
19 **Bazilian**, M. Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, R.S.J., Yumkella, K., ;  
20 Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy*, Volume 39, Issue 12, December  
21 2011, Pages 7896-7906
- 22 **Bierbaum**, R., and P. Matson, "Energy in the Context of Sustainability", Daedalus, The Alternative Energy Future, Vol.2, 90-97, 2013.
- 23 **Döll**, P., Hoffmann-Dobrev, H., Portmann, F.T., Siebert, S., Eicker, A., Rodell, M., Strassberg, G., Scanlon, B. (2012): Impact of water  
24 withdrawals from groundwater and surface water on continental water storage variations. *J. Geodyn.* 59-60, 143-156,  
25 doi:10.1016/j.jog.2011.05.001.
- 26 **Davies**, E., Page, K. and Edmonds, J. A., 2013. "An Integrated Assessment of Global and Regional Water Demands for Electricity Generation to  
27 2095." *Advances in Water Resources* 52:296–313.10.1016/j.advwatres.2012.11.020.
- 28 **Diffenbaugh**, N., Hertel, T., M. Scherer & M. Verma, "Response of corn markets to climate volatility under alternative energy futures", *Nature*  
29 *Climate Change* 2, 514–518 (2012)
- 30 **Gerten** D., Heinke H., Hoff H., Biemans H., Fader M., Waha K. (2011): Global water availability and requirements for future food production,  
31 *Journal of Hydrometeorology*, doi: 10.1175/2011JHM1328.1.
- 32 **Khan**, S., Hanjra, M. A. 2009. Footprints of water and energy inputs in food production - Global perspectives. *Food Policy*, 34, 130-140.
- 33 **King**, C. and Webber, M. E., Water intensity of transportation, *Environmental Science and Technology*, 2008, 42 (21), 7866-7872.
- 34 **Macknick**, J.; Newmark, R.; Heath, G.; Hallett, K. C.; Meldrum, J.; Nettles-Anderson, S. (2012). Operational Water Consumption and  
35 Withdrawal Factors for Electricity Generating Technologies: A Review of Existing Literature", *Environmental Research Letters*. Vol. 7(4),  
36 2012a
- 37 **Macknick**, J.; Sattler, S.; Averyt, K.; Clemmer, S.; Rogers, J. (2012). Water Implications of Generating Electricity: Water Use Across the United  
38 States Based on Different Electricity Pathways through 2050." *Environmental Research Letters*. Vol. 7(4), 2012b
- 39 **McCornick** P.G., Awulachew S.B. and Abebe M. (2008): Water-food-energy-environment synergies and tradeoffs: major issues and case  
40 studies. *Water Policy*, 10: 23-36.
- 41 **Plappally**, A.K., and J.H. Lienhard V; Energy requirements for water production, treatment, end use, reclamation, and disposal; *Renewable and*  
42 *Sustainable Energy Reviews*, Volume 16, Issue 7, September 2012, Pages 4818-4848
- 43 **Pelletier**, N., Audsley, E. , Brodt, S. , Garnett, T., Henriksson, P., Kendall, A., Kramer, K.J. , Murphy, D., Nemeck, T. and M. Troell, "Energy  
44 Intensity of Agriculture and Food Systems", *Annual Review of Environment and Resources*, 36: 223-246, 2011.
- 45 **Sattler**, S.; Macknick, J.; Yates, D.; Flores-Lopez, F.; Lopez, A.; Rogers, J. (2012). Linking Electricity and Water Models to Assess Electricity  
46 Choices at Water-Relevant Scales. *Environmental Research Letters*. Vol. 7(4), October-December 2012
- 47 **Shah** T. (2007): Groundwater, a global assessment of scale and significance, in: Molden (ed) *Comprehensive Assessment of Water Management*  
48 *in Agriculture*, Earthscan, Colombo, International Water Management Institute.
- 49 **Skaggs**, R., Janetos, TC, Hibbard, KA , Rice, JS, Climate and Energy-Water-Land System Interactions; Technical Report to the U.S. Department  
50 of Energy in Support of the National Climate Assessment, PNNL report 21185, March 2012
- 51 **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  
52 climate change. *Nature Climate Change*, 2, 676–681(2012).
- 53 **Wise**, M., Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R., Smith, S.J., Janetos, A, Edmonds, J. 2009. Implications of limiting  
54 CO2 concentrations for land use and energy. *Science* 324, 1183-1186.

1 World Energy Council; Water for Energy; 2010.

2  
3  
4 **References**

- 5  
6 Aakala, T., Kuuluvainen, T., Wallenius, T., and Kauhanen, H., 2011: Tree mortality episodes in the intact Picea  
7 abies-dominated taiga in the Arkhangelsk region of northern European Russia. *Journal of Vegetation Science*,  
8 **22(2)**, 322-333.
- 9 Abatzoglou, J.T., and Kolden, C.A., 2011: Climate Change in Western US Deserts: Potential for Increased Wildfire  
10 and Invasive Annual Grasses. *Rangeland Ecology & Management*, **64(5)**, 471-478.
- 11 Adamik, P., and Kral, M., 2008: Climate- and resource-driven long-term changes in dormice populations negatively  
12 affect hole-nesting songbirds. *Journal of Zoology*, **275(3)**, 209-215.
- 13 Adamik, P., and Pietruszkova, J., 2008: Advances in spring but variable autumnal trends in timing of inland wader  
14 migration. *Acta Ornithologica*, **43(2)**, 119-128.
- 15 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.,  
16 2012: Ecohydrological consequences of drought- and infestation- triggered tree die-off: insights and  
17 hypotheses. *Ecohydrology*, **5(2)**, 145-159.
- 18 Adrian, R., O'Reilly, C.M., Zagarese, H., Baines, S.B., Hessen, D.O., Keller, W., Livingstone, D.M., Sommaruga,  
19 R., Straile, D., Van Donk, E., Weyhenmeyer, G.A., and Winder, M., 2009: Lakes as sentinels of climate change.  
20 *Limnology and Oceanography*, **54(6)**, 2283-2297.
- 21 Ahl, D.E., Gower, S.T., Burrows, S.N., Shabanov, N.V., Myneni, R.B., and Knyazikhin, Y., 2006: Monitoring  
22 spring canopy phenology of a deciduous broadleaf forest using MODIS. *Remote Sensing of Environment*,  
23 **104(1)**, 88-95.
- 24 Ahola, M.P., Laaksonen, T., Eeva, T., and Lehikoinen, E., 2007: Climate change can alter competitive relationships  
25 between resident and migratory birds. *Journal of Animal Ecology*, **76(6)**, 1045-1052.
- 26 Aiello-Lammens, M.E., Chu-Agor, M.L., Convertino, M., Fischer, R.A., Linkov, I., and Akcakaya, H.R., 2011: The  
27 impact of sea-level rise on Snowy Plovers in Florida: integrating geomorphological, habitat, and  
28 metapopulation models. *Global Change Biology*, **17(12)**, 3644-3654.
- 29 Ainsworth, E.A., Yendrek, C.R., Sitch, S., Collins, W.J., and Emberson, L.D., 2012: The Effects of Tropospheric  
30 Ozone on Net Primary Productivity and Implications for Climate Change. *Annual Review of Plant Biology*,  
31 **63(1)**, 637-661.
- 32 Akcakaya, H.R., Butchart, S.H.M., Mace, G.M., Stuart, S.N., and Hilton-Taylor, C., 2006: Use and misuse of the  
33 IUCN Red List Criteria in projecting climate change impacts on biodiversity. *Global Change Biology*, **12(11)**,  
34 2037-2043.
- 35 Alahuhta, J., Heino, J., and Luoto, M., 2011: Climate change and the future distributions of aquatic macrophytes  
36 across boreal catchments. *Journal of Biogeography*, **38(2)**, 383-393.
- 37 Albert, K.R., Kongstad, J., Schmidt, I.K., Ro-Poulsen, H., Mikkelsen, T.N., Michelsen, A., van der Linden, L., and  
38 Beier, C., 2012: Temperate heath plant response to dry conditions depends on growth strategy and less on  
39 physiology. *Acta Oecologica-International Journal of Ecology*, **45**, 79-87.
- 40 Albert, K.R., Ro-Poulsen, H., Mikkelsen, T.N., Michelsen, A., Van der Linden, L., and Beier, C., 2011: Effects of  
41 elevated CO<sub>2</sub>, warming and drought episodes on plant carbon uptake in a temperate heath ecosystem are  
42 controlled by soil water status. *Plant Cell and Environment*, **34(7)**, 1207-1222.
- 43 Aldous, A., Fitzsimons, J., Richter, B., and Bach, L., 2011: Droughts, floods and freshwater ecosystems: evaluating  
44 climate change impacts and developing adaptation strategies. *Marine and Freshwater Research*, **62(3)**, 223-231.
- 45 Alencar, A., Asner, G.P., Knapp, D., and Zarin, D., 2011: Temporal variability of forest fires in eastern Amazonia.  
46 *Ecological Applications*, **21(7)**, 2397-2412.
- 47 Alencar, A., Nepstad, D.C., and Vera Diaz, M.d.C., 2006: Forest understory fire in the Brazilian Amazon in ENSO  
48 and non-ENSO Years: Area burned and committed carbon emissions. *Earth Interactions*, **10(6)**, 1-17.
- 49 Alexander, H.D., Mack, M.C., Goetz, S., Loranty, M., Beck, P.S.A., and Earl, K., 2012: Effects of successional  
50 stage and tree density on carbon accumulation patterns of post-fire Cajander larch (*Larix cajanderi*) forests  
51 within Far Northeastern Siberia. *Ecosphere*.
- 52 Ali, A.A., Blarquez, O., Girardin, M.P., Hely, C., Tinquaut, F., El Guellab, A., Valsecchi, V., Terrier, A., Bremond,  
53 L., Genries, A., Gauthier, S., and Bergeron, Y., 2012: Control of the multimillennial wildfire size in boreal

- 1 North America by spring climatic conditions. *Proceedings of the National Academy of Sciences of the United*  
2 *States of America*, **109(51)**, 20966-20970.
- 3 Alkama, R., Kageyama, M., and Ramstein, G., 2012: A sensitivity study to global desertification in cold and warm  
4 climates: results from the IPSL OAGCM model. *Climate Dynamics*, **38(7-8)**, 1629-1647.
- 5 Alkemade, R., van Oorschot, M., Miles, L., Nellemann, C., Bakkenes, M., and ten Brink, B., 2009: GLOBIO3: A  
6 Framework to Investigate Options for Reducing Global Terrestrial Biodiversity Loss. *Ecosystems*, **12(3)**, 374-  
7 390.
- 8 Allan, J.D., 2004: Landscapes and riverscapes: The influence of land use on stream ecosystems. *Annual Review of*  
9 *Ecology Evolution and Systematics*, **35**, 257-284.
- 10 Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling,  
11 A., Breshears, D.D., Hogg, E.H., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.H.,  
12 Allard, G., Running, S.W., Semerci, A., and Cobb, N., 2010a: A global overview of drought and heat-induced  
13 tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, **259(4)**, 660-  
14 684.
- 15 Allen, J.R.M., Hickler, T., Singarayer, J.S., Sykes, M.T., Valdes, P.J., and Huntley, B., 2010b: Last glacial  
16 vegetation of northern Eurasia. *Quaternary Science Reviews*, **29(19-20)**, 2604-2618.
- 17 Alley, R.B., Marotzke, J., Nordhaus, W.D., Overpeck, J.T., Peteet, D.M., Pielke, R.A., Pierrehumbert, R.T., Rhines,  
18 P.B., Stocker, T.F., Talley, L.D., and Wallace, J.M., 2003: Abrupt climate change. *Science*, **299(5615)**, 2005-  
19 2010.
- 20 Anchukaitis, K.J., and Evans, M.N., 2010: Tropical cloud forest climate variability and the demise of the  
21 Monteverde golden toad. *Proceedings of the National Academy of Sciences of the United States of America*,  
22 **107(11)**, 5036-5040.
- 23 Anderegg, W.R.L., Anderegg, L.D.L., Sherman, C., and Karp, D.S., 2012: Effects of Widespread Drought-Induced  
24 Aspen Mortality on Understory Plants. *Conservation Biology*, **26(6)**, 1082-1090.
- 25 Anderegg, W.R.L., Kane, J.M., and Anderegg, L.D.L., 2013a: Consequences of widespread tree mortality triggered  
26 by drought and temperature stress. *Nature Climate Change*, **3(1)**, 30-36.
- 27 Anderegg, W.R.L., Plavcová, L., Anderegg, L.D.L., Hacke, U.G., Berry, J.A., and Field, C.B., 2013b: Drought's  
28 legacy: multiyear hydraulic deterioration underlies widespread aspen forest die-off and portends increased  
29 future risk. *Global Change Biology*, n/a-n/a.
- 30 Anderson, J.T., Inouye, D.W., McKinney, A.M., Colautti, R.I., and Mitchell-Olds, T., 2012a: Phenotypic plasticity  
31 and adaptive evolution contribute to advancing flowering phenology in response to climate change. *Proceedings*  
32 *of the Royal Society B-Biological Sciences*, **279(1743)**, 3843-3852.
- 33 Anderson, J.T., Panetta, A.M., and Mitchell-Olds, T., 2012b: Evolutionary and Ecological Responses to  
34 Anthropogenic Climate Change. *Plant Physiology*, **160(4)**, 1728-1740.
- 35 Anderson, R.G., Canadell, J.G., Randerson, J.T., Jackson, R.B., Hungate, B.A., Baldocchi, D.D., Ban-Weiss, G.A.,  
36 Bonan, G.B., Caldeira, K., Cao, L., Diffenbaugh, N.S., Gurney, K.R., Kueppers, L.M., Law, B.E., Luysaert, S.,  
37 and O'Halloran, T.L., 2011: Biophysical considerations in forestry for climate protection. *Frontiers in Ecology*  
38 *and the Environment*, **9(3)**, 174-182.
- 39 Andreae, M.O., Rosenfeld, D., Artaxo, P., Costa, A.A., Frank, G.P., Longo, K.M., and Silva-Dias, M.A.F., 2004:  
40 Smoking rain clouds over the Amazon. *Science*, **303**, 1337-1342.
- 41 Andreu-Hayles, L., Planells, O., GutiÉRrez, E., Muntan, E., Helle, G., Anchukaitis, K.J., and Schleser, G.H., 2011:  
42 Long tree-ring chronologies reveal 20th century increases in water-use efficiency but no enhancement of tree  
43 growth at five Iberian pine forests. *Global Change Biology*, **17(6)**, 2095-2112.
- 44 Angassa, A., and Oba, G., 2008: Effects of management and time on mechanisms of bush encroachment in southern  
45 Ethiopia. *African Journal of Ecology*, **46(2)**, 186-196.
- 46 Angeler, D.G., and Goedkoop, W., 2010: Biological responses to liming in boreal lakes: an assessment using  
47 plankton, macroinvertebrate and fish communities. *Journal of Applied Ecology*, **47(2)**, 478-486.
- 48 Angert, A.L., Crozier, L.G., Rissler, L.J., Gilman, S.E., Tewksbury, J.J., and Chunco, A.J., 2011: Do species' traits  
49 predict recent shifts at expanding range edges? *Ecology Letters*, **14(7)**, 677-689.
- 50 Angetter, L.S., Lotters, S., and Rodder, D., 2011: Climate niche shift in invasive species: the case of the brown  
51 anole. *Biological Journal of the Linnean Society*, **104(4)**, 943-954.
- 52 Anyamba, A., and Tucker, C.J., 2005: Analysis of Sahelian vegetation dynamics using NOAAVHRR NDVI data  
53 from 1981-2003. *Journal of Arid Environments*, **63(3)**, 596-614.

- 1 Aragão, L., Malhi, Y., Barbier, N., Lima, A., Shimabukuro, Y., Anderson, L., and Saatchi, S., 2008: Interactions  
2 between rainfall, deforestation and fires during recent years in the Brazilian Amazonia. *Philosophical*  
3 *Transactions of the Royal Society B-Biological Sciences*, **363(1498)**, 1779-1785.
- 4 Araujo, M.B., Alagador, D., Cabeza, M., Nogues-Bravo, D., and Thuiller, W., 2011: Climate change threatens  
5 European conservation areas. *Ecology Letters*, **14(5)**, 484-492.
- 6 Araujo, M.B., and Peterson, A.T., 2012: Uses and misuses of bioclimatic envelope modeling. *Ecology*, **93(7)**, 1527-  
7 1539.
- 8 Archibald, S., Roy, D.P., van Wilgen, B.W., and Scholes, R.J., 2009: What limits fire? An examination of drivers of  
9 burnt area in southern Africa. *Global Change Biology*, **15(3)**, 613-630.
- 10 Arenas, M., Ray, N., Currat, M., and Excoffier, L., 2012: Consequences of Range Contractions and Range Shifts on  
11 Molecular Diversity. *Molecular Biology and Evolution*, **29(1)**, 207-218.
- 12 Armenteras-Pascual, D., Retana-Alumbreros, J., Molowny-Horas, R., Roman-Cuesta, R.M., Gonzalez-Alonso, F.,  
13 and Morales-Rivas, M., 2011: Characterising fire spatial pattern interactions with climate and vegetation in  
14 Colombia. *Agricultural and Forest Meteorology*, **151(3)**, 279-289.
- 15 Arneeth, A., Harrison, S.P., Zaehle, S., Tsigaridis, K., Menon, S., Bartlein, P.J., Feichter, J., Korhola, A., Kulmala,  
16 M., O'Donnell, D., Schurgers, G., Sorvari, S., and Vesala, T., 2010: Terrestrial biogeochemical feedbacks in the  
17 climate system. *Nature Geoscience*, **3(8)**, 525-532.
- 18 Arora, V.K., and Montenegro, A., 2011: Small temperature benefits provided by realistic afforestation efforts.  
19 *Nature Geoscience*, **4(8)**, 514-518.
- 20 Axford, Y., Briner, J.P., Cooke, C.A., Francis, D.R., Michelutti, N., Miller, G.H., Smol, J.P., Thomas, E.K., Wilson,  
21 C.R., and Wolfe, A.P., 2009: Recent changes in a remote Arctic lake are unique within the past 200,000 years.  
22 *Proceedings of the National Academy of Sciences of the United States of America*, **106(44)**, 18443-18446.
- 23 Baccini, A., Goetz, S.J., Walker, W.S., Laporte, N.T., Sun, M., Sulla-Menashe, D., Hackler, J., Beck, P.S.A.,  
24 Dubayah, R., Fiedl, M.A., Samanta, S., and Houghton, R.A., 2012: Estimated carbon dioxide emissions from  
25 tropical deforestation improved by carbon-density maps. *Nature Climate Change*, **2(3)**, 182-185.
- 26 Bai, Z.G., Dent, D.L., Olsson, L., and Schaepman, M.E., 2008: Proxy global assessment of land degradation. *Soil*  
27 *Use and Management*, **24(3)**, 223-234.
- 28 Balch, J.K., Nepstad, D.C., Brando, P.M., Curran, L.M., Portela, O., de Carvalho, O., and Lefebvre, P., 2008:  
29 Negative fire feedback in a transitional forest of southeastern Amazonia. *Global Change Biology*, **14(10)**, 2276-  
30 2287.
- 31 Balian, E.V., Segers, H., Leveque, C., and Martens, K., 2008: The freshwater animal diversity assessment: An  
32 overview of the results. *Hydrobiologia*, **595(1)**, 627-637.
- 33 Balint, M., Domisch, S., Engelhardt, C.H.M., Haase, P., Lehrian, S., Sauer, J., Theissing, K., Pauls, S.U., and  
34 Nowak, C., 2011: Cryptic biodiversity loss linked to global climate change. *Nature Climate Change*, **1(6)**, 313-  
35 318.
- 36 Ball, J.T., Woodrow, I.E., and Berry, J.A. (eds.), 1987: *A model predicting stomatal conductance and its to the*  
37 *control of photosynthesis under different environmental conditions*. Martinus Nijhoff Publishers, Netherlands,  
38 pp.
- 39 Barber, V.A., Juday, G.P., and Finney, B.P., 2000: Reduced growth of Alaskan white spruce in the twentieth century  
40 from temperature-induced drought stress. *Nature*, **405(6787)**, 668-673.
- 41 Barbet-Massin, M., Thuiller, W., and Jiguet, F., 2012: The fate of European breeding birds under climate, land-use  
42 and dispersal scenarios. *Global Change Biology*, **18(3)**, 881-890.
- 43 Barbosa, I.C.R., Koehler, I.H., Auerswald, K., Lups, P., and Hans, S., 2010: Last-century changes of alpine  
44 grassland water-use efficiency: a reconstruction through carbon isotope analysis of a time-series of *Capra ibex*  
45 horns. *Global Change Biology*, **16(4)**, 1171-1180.
- 46 Barbour, M., Keeler-Wolf, T., and Schoenherr, A.A., 2007: *Terrestrial vegetation of California*. University of  
47 California Presspp.
- 48 Barbraud, C., Gavriilo, M., Mizin, Y., and Weimerskirch, H., 2011: Comparison of emperor penguin declines  
49 between Pointe Geologie and Haswell Island over the past 50 years. *Antarctic Science*, **23(5)**, 461-468.
- 50 Barbraud, C., and Weimerskirch, H., 2006: Antarctic birds breed later in response to climate change. *Proceedings of*  
51 *the National Academy of Sciences of the United States of America*, **103(16)**, 6248-6251.
- 52 Barlow, J., and Peres, C.A., 2008: Fire-mediated dieback and compositional cascade in an Amazonian forest.  
53 *Philosophical Transactions of the Royal Society B-Biological Sciences*, **363(1498)**, 1787-1794.

- 1 Barnett, T.P., Adam, J.C., and Lettenmaier, D.P., 2005: Potential impacts of a warming climate on water availability  
2 in snow-dominated regions. *Nature*, **438(7066)**, 303-309.
- 3 Barnosky, A.D., Matzke, N., Tomiya, S., Wogan, G.O.U., Swartz, B., Quental, T.B., Marshall, C., McGuire, J.L.,  
4 Lindsey, E.L., Maguire, K.C., Mersey, B., and Ferrer, E.A., 2011: Has the Earth's sixth mass extinction already  
5 arrived? *Nature*, **471(7336)**, 51-57.
- 6 Bartholow, J.M., 2005: Recent water temperature trends in the lower Klamath River, California. *North American*  
7 *Journal of Fisheries Management*, **25(1)**, 152-162.
- 8 Battarbee, R.W., Kernan, M., and Rose, N., 2009: Threatened and stressed mountain lakes of Europe: Assessment  
9 and progress. *Aquatic Ecosystem Health & Management*, **12(2)**, 118-128.
- 10 Beaumont, L.J., Pitman, A., Perkins, S., Zimmermann, N.E., Yoccoz, N.G., and Thuiller, W., 2011: Impacts of  
11 climate change on the world's most exceptional ecoregions. *Proceedings of the National Academy of Sciences of*  
12 *the United States of America*, **108(6)**, 2306-2311.
- 13 Beck, H.E., McVicar, T.R., van Dijk, A.I.L., Schellenkens, J., de Jeu, R.A.M., and Bruijnzeel, L.A., 2011a: Global  
14 evaluation of four AVHRR-NDVI data sets: Intercomparison and assessment against Landsat imagery. *Remote*  
15 *Sensing of Environment*, **115(10)**, 2547-2563.
- 16 Beck, P.S.A., and Goetz, S.J., 2011: Satellite observations of high northern latitude vegetation productivity changes  
17 between 1982 and 2008: ecological variability and regional differences. *Environmental Research Letters*, **6(4)**.
- 18 Beck, P.S.A., Juday, G.P., Claire, A., Steve, W., Emily, S., Patricia, H., James, D.H., and Goetz, S.J., 2011b:  
19 Changes in forest productivity across Alaska are captured in satellite and tree ring records. *Ecology Letters*,  
20 **14(4)**, 373-379.
- 21 Beckage, B., Osborne, B., Gavin, D.G., Pucko, C., Siccama, T., and Perkins, T., 2008: A rapid upward shift of a  
22 forest ecotone during 40 years of warming in the Green Mountains of Vermont. *Proceedings of the National*  
23 *Academy of Sciences of the United States of America*, **105(11)**, 4197-4202.
- 24 Beerling, D.J., and Osborne, C.P., 2006: The origin of the savanna biome. *Global Change Biology*, **12(11)**, 2023-  
25 2031.
- 26 Beier, C., Emmett, B.A., Penuelas, J., Schmidt, I.K., Tietema, A., Estiarte, M., Gundersen, P., Llorens, L., Riis-  
27 Nielsen, T., Sowerby, A., and Gorissen, A., 2008: Carbon and nitrogen cycles in European ecosystems respond  
28 differently to global warming. *Science of the Total Environment*, **407(1)**, 692-697.
- 29 Beier, C., Schmidt, I.K., and Kristensen, H.L., 2004: Effects of climate and ecosystem disturbances on  
30 biogeochemical cycling in a semi-natural terrestrial ecosystem. *Water, Air and Soil Pollution: Focus*, **4**, 191-  
31 206.
- 32 Beilman, D.W., MacDonald, G.M., Smith, L.C., and Reimer, P.J., 2009: Carbon accumulation in peatlands of West  
33 Siberia over the last 2000 years. *Global Biogeochemical Cycles*, **23(GB1012)**, doi:10.1029/2007GB003112).
- 34 Bell, G., 2013: Evolutionary rescue and the limits of adaptation. *Philosophical Transactions of the Royal Society B-*  
35 *Biological Sciences*, **368(1610)**.
- 36 Bell, G., and Gonzalez, A., 2009: Evolutionary rescue can prevent extinction following environmental change.  
37 *Ecology Letters*, **12(9)**, 942-948.
- 38 Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., and Courchamp, F., 2012: Impacts of climate change on the  
39 future of biodiversity. *Ecology Letters*, **15(4)**, 365-377.
- 40 Bellassen, V., Viovy, N., Luyssaert, S., Le Maire, G., Schelhaas, M.J., and Ciais, P., 2011: Reconstruction and  
41 attribution of the carbon sink of European forests between 1950 and 2000. *Global Change Biology*, **17(11)**,  
42 3274-3292.
- 43 Belyazid, S., Kurz, D., Braun, S., Sverdrup, H., Rihm, B., and Hettelingh, J.P., 2011: A dynamic modelling  
44 approach for estimating critical loads of nitrogen based on pliant community changes under a changing climate.  
45 *Environmental Pollution*, **159(3)**, 789-801.
- 46 Bentz, B.J., Régnière, J., Fettig, C.J., Hansen, E.M., Hayes, J.L., Hicke, J.A., Kelsey, R.G., Negrón, J.F., and  
47 Seybold, S.J., 2010: Climate Change and Bark Beetles of the Western United States and Canada: Direct and  
48 Indirect Effects. *Bioscience*, **60(8)**, 602-613.
- 49 Bergstrom, A.K., and Jansson, M., 2006: Atmospheric nitrogen deposition has caused nitrogen enrichment and  
50 eutrophication of lakes in the northern hemisphere. *Global Change Biology*, **12**, 635-643.
- 51 Berkes, F., Colding, J., and Folke, C. (eds.), 2003: *Navigating social-ecological Systems. Building Resilience for*  
52 *Complexity and Change*. University Press, Cambridge, pp.
- 53 Bernacchi, C.J., Leakey, A.D.B., Heady, L.E., Morgan, P.B., Dohleman, F.G., McGrath, J.M., Gillespie, K.M.,  
54 Wittig, V.E., Rogers, A., Long, S.P., and Ort, D.R., 2006: Hourly and seasonal variation in photosynthesis and

- 1 stomatal conductance of soybean grown at future CO<sub>2</sub> and ozone concentrations for 3 years under fully open-  
2 air field conditions. *Plant Cell and Environment*, **29(11)**, 2077-2090.
- 3 Bernhardt, E.L., Hollingsworth, T.N., and Chapin III, F.S., 2011: Fire severity mediates climate-driven shifts in  
4 understory community composition of black spruce stands of interior Alaska. *Journal of Vegetation Science*,  
5 **22(1)**, 32-44.
- 6 Bertaux, D., Reale, D., McAdam, A.G., and Boutin, S., 2004: Keeping pace with fast climate change: can arctic life  
7 count on evolution? *Integrative and Comparative Biology*, **44(2)**, 140-151.
- 8 Bertelsmeier, C., Luque, G., and Courchamp, F., 2012: Global warming may freeze the invasion of big-headed ants.  
9 *Biological Invasions*, 1-12.
- 10 Bertrand, R., Lenoir, J., Piedallu, C., Riofrio-Dillon, G., de Ruffray, P., Vidal, C., Pierrat, J.C., and Gegout, J.C.,  
11 2011: Changes in plant community composition lag behind climate warming in lowland forests. *Nature*,  
12 **479(7374)**, 517-520.
- 13 Betts, R.A., Arnell, N.W., Boorman, P., Cornell, S.E., House, J.I., Kaye, N.R., McCarthy, M.P., McNeall, D.,  
14 Sanderson, M.G., and Wiltshire, A.J., 2012: Climate change impacts and adaptation: an Earth system view.  
15 Understanding the Earth System: Global Change Science for Application. . In *Understanding the Earth System:  
16 Global Change Science for Application*. [S. Cornell, C. Prentice, J. House & C. Downy (eds.)]. Cambridge  
17 University Press, Cambridge, pp. 160-201.
- 18 Betts, R.A., Golding, N., Gonzalez, P., Gornall, J., Kahana, R., Kay, G., Mitchell, L., and Wiltshire, A., submitted:  
19 Climate and land use change impacts on global terrestrial ecosystems, fire, and river flows in the HadGEM2-ES  
20 Earth System Model using the Representative Concentration Pathways.
- 21 Bhatt, U.S., Walker, D.A., Reynolds, M.K., Comiso, J.C., Epstein, H.E., Jia, G.S., Gens, R., Pinzon, J.E., Tucker,  
22 C.J., Tweedie, C.E., and Webber, P.J., 2010: Circumpolar Arctic Tundra Vegetation Change Is Linked to Sea  
23 Ice Decline. *Earth Interactions*, **14(8)**, 1-20.
- 24 Biesmeijer, J.C., Roberts, S.P.M., Reemer, M., Ohlemuller, R., Edwards, M., Peeters, T., Schaffers, A.P., Potts,  
25 S.G., Kleukers, R., Thomas, C.D., Settele, J., and Kunin, W.E., 2006: Parallel declines in pollinators and insect-  
26 pollinated plants in Britain and the Netherlands. *Science*, **313(5785)**, 351-354.
- 27 Biggs, D., Biggs, R., Dakos, V., Scholes, R.J., and Schoon, M., 2011: Are We Entering an Era of Concatenated  
28 Global Crises? *Ecology and Society*, **16(2)**.
- 29 Biggs, R., Carpenter, S.R., and Brock, W.A., 2009: Turning back from the brink: Detecting an impending regime  
30 shift in time to avert it. *Proceedings of the National Academy of Sciences of the United States of America*,  
31 **106(3)**, 826-831.
- 32 Birdsey, R.A., Pregitzer, K.S., and Lucier, A., 2006: Forest carbon management in the United States: 1600-2100.  
33 *Journal of Environmental Quality*, **35(4)**, 1461-1469.
- 34 Birks, H.J.B., and Willis, K.J., 2008: Alpines, trees, and refugia in Europe. *Plant Ecology & Diversity*, **1(2)**, 147-  
35 160.
- 36 Bleeker, A., Hicks, W.K., Dentener, E., Galloway, J., and Erisman, J.W., 2011: N deposition as a threat to the  
37 World's protected areas under the Convention on Biological Diversity. *Environmental Pollution*, **159(10)**, 2280-  
38 2288.
- 39 Blok, D., Heijmans, M.M.P.D., Schaepman-Strub, G., Kononov, A.V., Maximov, T.C., and Berendse, F., 2010:  
40 Shrub expansion may reduce summer permafrost thaw in Siberian tundra. *Global Change Biology*, **16(4)**, 1296-  
41 1305.
- 42 Bloor, J., Pichon, P., Falcimagne, R., Leadley, P., and Soussana, J.-F., 2010: Effects of Warming, Summer Drought,  
43 and CO<sub>2</sub> Enrichment on Aboveground Biomass Production, Flowering Phenology, and  
44 Community Structure in an Upland Grassland Ecosystem. *Ecosystems*, **13(6)**, 888-900.
- 45 BMT WBM, 2010: *Kakadu - Vulnerability to climate change impacts. A report to the Australian Government  
46 Department of Climate Change and Energy Efficiency*. 1-226 pp.
- 47 Bobbink, R., Hicks, K., Galloway, J., Spranger, T., Alkemade, R., Ashmore, M., Bustamante, M., Cinderby, S.,  
48 Davidson, E., Dentener, F., Emmett, B., Erisman, J.W., Fenn, M., Gilliam, F., Nordin, A., Pardo, L., and De  
49 Vries, W., 2010: Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis.  
50 *Ecological Applications*, **20(1)**, 30-59.
- 51 Boggs, C.L., and Inouye, D.W., 2012: A single climate driver has direct and indirect effects on insect population  
52 dynamics. *Ecology Letters*, **15(5)**, 502-508.
- 53 Boisvenue, C., and Running, S.W., 2006: Impacts of climate change on natural forest productivity - evidence since  
54 the middle of the 20th century. *Global Change Biology*, **12(5)**, 862-882.



- 1 Bolte, A., Ammer, C., Lof, M., Madsen, P., Nabuurs, G.J., Schall, P., Spathelf, P., and Rock, J., 2009: Adaptive  
2 forest management in central Europe: Climate change impacts, strategies and integrative concept. *Scandinavian*  
3 *Journal of Forest Research*, **24(6)**, 473-482.
- 4 Bolte, A., and Degen, B., 2010: Forest adaptation to climate change - options and limitations. *Landbauforschung*,  
5 **60(3)**, 111-117.
- 6 Bolte, A., Hilbrig, L., Grundmann, B., Kampf, F., Brunet, J., and Roloff, A., 2010: Climate change impacts on stand  
7 structure and competitive interactions in a southern Swedish spruce-beech forest. *European Journal of Forest*  
8 *Research*, **129(3)**, 261-276.
- 9 Bomhard, B., Richardson, D.M., Donaldson, J.S., Hughes, G.O., Midgley, G.F., Raimondo, D.C., Rebelo, A.G.,  
10 Rouget, M., and Thuiller, W., 2005: Potential impacts of future land use and climate change on the Red List  
11 status of the Proteaceae in the Cape Floristic Region, South Africa. *Global Change Biology*, **11(9)**, 1452-1468.
- 12 Bonan, G.B., 2008: Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests. *Science*,  
13 **320(5882)**, 1444-1449.
- 14 Bond-Lamberty, B., Peckham, S.D., Ahl, D.E., and Gower, S.T., 2007: Fire as the dominant driver of central  
15 Canadian boreal forest carbon balance. *Nature*, **450(7166)**, 89-92
- 16 Bond-Lamberty, B., and Thomson, A., 2010: Temperature-associated increases in the global soil respiration record.  
17 *Nature*, **464(7288)**, 579-582.
- 18 Bond, N.R., Lake, P.S., and Arthington, A.H., 2008: The impacts of drought on freshwater ecosystems: an  
19 Australian perspective. *Hydrobiologia*, **600(1)**, 3-16.
- 20 Bond, W.J., and Midgley, G.F., 2012: Carbon dioxide and the uneasy interactions of trees and savannah grasses.  
21 *Philos Trans R Soc Lond B Biol Sci*, **367(1588)**, 601-612.
- 22 Bond, W.J., and Midgley, J.J., 2001: Ecology of sprouting in woody plants: the persistence niche. *Trends in Ecology*  
23 *& Evolution*, **16(1)**, 45-51.
- 24 Bonfils, C.J.W., Phillips, T.J., Lawrence, D.M., Cameron-Smith, P., Riley, W.J., and Subin, Z.M., 2012: On the  
25 influence of shrub height and expansion on northern high latitude climate. *Environmental Research Letters*,  
26 **7(1)**.
- 27 Bontemps, J.D., Herve, J.C., Leban, J.M., and Dhote, J.F., 2011: Nitrogen footprint in a long-term observation of  
28 forest growth over the twentieth century. *Trees-Structure and Function*, **25(2)**, 237-251.
- 29 Booth, R.K., Jackson, S.T., Forman, S.L., Kutzbach, J.E., Bettis, E.A., Kreig, J., and Wright, D.K., 2005: A severe  
30 centennial-scale drought in mid-continental North America 4200 years ago and apparent global linkages.  
31 *Holocene*, **15(3)**, 321-328.
- 32 Both, C., Bouwhuis, S., Lesselis, C.M., and Visser, M.E., 2006: Climate change and population declines in a long-  
33 distance migratory bird. *Nature*, **441(7089)**, 81-83.
- 34 Both, C., Van Turnhout, C.A.M., Bijlsma, R.G., Siepel, H., Van Strien, A.J., and Foppen, R.P.B., 2010: Avian  
35 population consequences of climate change are most severe for long-distance migrants in seasonal habitats.  
36 *Proceedings of the Royal Society B-Biological Sciences*, **277(1685)**, 1259-1266.
- 37 Both, C., and Visser, M.E., 2001: Adjustment to climate change is constrained by arrival date in a long-distance  
38 migrant bird. *Nature*, **411(6835)**, 296-298.
- 39 Botkin, D.B., Saxe, H., Araujo, M.B., Betts, R., Bradshaw, R.H.W., Cedhagen, T., Chesson, P., Dawson, T.P.,  
40 Etterson, J.R., Faith, D.P., Ferrier, S., Guisan, A., Hansen, A.S., Hilbert, D.W., Loehle, C., Margules, C., New,  
41 M., Sobel, M.J., and Stockwell, D.R.B., 2007: Forecasting the effects of global warming on biodiversity.  
42 *Bioscience*, **57(3)**, 227-236.
- 43 Boucher, O., Randall, D., and Others, in preparation: Clouds and Aerosols. In *The Physical Science Basis:*  
44 *Contribution of Working Group 1 to the 5th Assessment Report of the Intergovernmental Panel on Climate*  
45 *Change* [T. F. Stocker (ed.)]. pp.
- 46 Boutton, T.W., Liao, J.D., Filley, T.R., and Archer, S.R., 2009: Belowground carbon storage and dynamics  
47 accompanying woody plant encroachment in a subtropical savanna. In *Soil Carbon Sequestration and the*  
48 *Greenhouse Effect*. Madison, WI, pp. 181-205.
- 49 Bowman, D., Balch, J.K., Artaxo, P., Bond, W.J., Carlson, J.M., Cochrane, M.A., D'Antonio, C.M., DeFries, R.S.,  
50 Doyle, J.C., Harrison, S.P., Johnston, F.H., Keeley, J.E., Krawchuk, M.A., Kull, C.A., Marston, J.B., Moritz,  
51 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  
52 the Earth System. *Science*, **324(5926)**, 481-484.
- 53 Bowman, D.M.J.S., Murphy, B.P., and Banfai, D.S., 2011: Has global environmental change caused monsoon  
54 rainforests to expand in the Australian monsoon tropics? *Landscape Ecology*, **25(8)**, 1247-1260.

- 1 Bradley, B.A., Blumenthal, D.M., Wilcove, D.S., and Ziska, L.H., 2010: Predicting plant invasions in an era of  
2 global change. *Trends in Ecology & Evolution*, **25(5)**, 310-318.
- 3 Bradley, B.A., Oppenheimer, M., and Wilcove, D.S., 2009: Climate change and plant invasions: restoration  
4 opportunities ahead? *Global Change Biology*, **15(6)**, 1511-1521.
- 5 Bradley, N.L., Leopold, A.C., Ross, J., and Huffnaker, W., 1999: Phenological changes reflect climate change in  
6 Wisconsin. *Proceedings of the National Academy of Sciences of the United States of America*, **96(17)**, 9701-  
7 9704.
- 8 Bradshaw, W.E., and Holzapfel, C.M., 2006: Evolutionary response to rapid climate change. *Science*, **312(5779)**,  
9 1477-1478.
- 10 Brandão, R.A., and Araújo, A.F.B., 2007: Changes in Anuran Species Richness and Abundance Resulting from  
11 Hydroelectric Dam Flooding in Central Brazil. *Biotropica*, **40(2)**, 263-266.
- 12 Brando, P.M., Goetz, S.J., Baccini, A., Nepstad, D.C., Beck, P.S.A., and Christman, M.C., 2010: Seasonal and  
13 interannual variability of climate and vegetation indices across the Amazon. *Proceedings of the National  
14 Academy of Sciences of the United States of America*, **107(33)**, 14685-14690.
- 15 Brando, P.M., Nepstad, D.C., Balch, J.K., Bolker, B., Christman, M.C., Coe, M.T., and Putz, F.E., 2012: Fire-  
16 induced tree mortality in a neotropical forest: the roles of bark traits, tree size, wood density and fire behavior.  
17 *Global Change Biology*, **18(2)**, 630-641.
- 18 Brasier, C., and Webber, J., 2010: Plant pathology: Sudden larch death. *Nature*, **466(7308)**, 824-825.
- 19 Breshears, D.D., 2006: The grassland-forest continuum: trends in ecosystem properties for woody plant mosaics?  
20 *Frontiers in Ecology and the Environment*, **4(2)**, 96-104.
- 21 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,  
22 M.L., Belnap, J., Anderson, J.J., Myers, O.B., and Meyer, C.W., 2005: Regional vegetation die-off in response  
23 to global-change-type drought. *Proceedings of the National Academy of Sciences of the United States of  
24 America*, **102(42)**, 15144-15148.
- 25 Bridle, J.R., Polechova, J., Kawata, M., and Butlin, R.K., 2010: Why is adaptation prevented at ecological margins?  
26 New insights from individual-based simulations. *Ecology Letters*, **13(4)**, 485-494.
- 27 Briffa, K.R., Shishov, V.V., Melvin, T.M., Vaganov, E.A., Grudd, H., Hantemirov, R.M., Eronen, M., and  
28 Naurzbaev, M.M., 2008: Trends in recent temperature and radial tree growth spanning 2000 years across  
29 northwest Eurasia. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **363(1501)**, 2271-  
30 2284.
- 31 Brink, V.C., 1959: A Directional Change in the Subalpine Forest-Heath Ecotone in Garibaldi Park, British  
32 Columbia. *Ecology*, **40(1)**, 10-16.
- 33 Brisson, J., de Blois, S., and Lavoie, C., 2010: Roadside as Invasion Pathway for Common Reed (*Phragmites  
34 australis*). *Invasive Plant Science and Management*, **3(4)**, 506-514.
- 35 Brittain, C., Bommarco, R., Vighi, M., Barmaz, S., Settele, J., and Potts, S.G., 2010a: The impact of an insecticide  
36 on insect flower visitation and pollination in an agricultural landscape. *Agricultural and Forest Entomology*,  
37 **12(3)**, 259-266.
- 38 Brittain, C.A., Vighi, M., Bommarco, R., Settele, J., and Potts, S.G., 2010b: Impacts of a pesticide on pollinator  
39 species richness at different spatial scales. *Basic and Applied Ecology*, **11(2)**, 106-115.
- 40 Britton, A.J., Beale, C.M., Towers, W., and Hewison, R.L., 2009: Biodiversity gains and losses: Evidence for  
41 homogenisation of Scottish alpine vegetation. *Biological Conservation*, **142(8)**, 1728-1739.
- 42 Britton, J.R., Cucherousset, J., Davies, G.D., Godard, M.J., and Copp, G.H., 2010: Non-native fishes and climate  
43 change: predicting species responses to warming temperatures in a temperate region. *Freshwater Biology*,  
44 **55(5)**, 1130-1141.
- 45 Broadmeadow, M.S.J., Ray, D., and Samuel, C.J.A., 2005: Climate change and the future for broadleaved tree  
46 species in Britain. *Forestry*, **78(2)**, 145-161.
- 47 Broennimann, O., Treier, U.A., Muller-Scharer, H., Thuiller, W., Peterson, A.T., and Guisan, A., 2007: Evidence of  
48 climatic niche shift during biological invasion. *Ecology Letters*, **10(8)**, 701-709.
- 49 Brommer, J.E., Lehikoinen, A., and Valkama, J., 2012: The Breeding Ranges of Central European and Arctic Bird  
50 Species Move Poleward. *PLoS One*, **7(9)**.
- 51 Bronson, D.R., Gower, S.T., Tanner, M., and Van Herk, I., 2009: Effect of ecosystem warming on boreal black  
52 spruce bud burst and shoot growth. *Global Change Biology*, **15(6)**, 1534-1543.
- 53 Brook, B.W., 2008: Synergies between climate change, extinctions and invasive vertebrates. *Wildlife Research*,  
54 **35(3)**, 249-252.

- 1 Brook, B.W., and Bowman, D.M.J.S., 2006: Postcards from the past: charting the landscape-scale conversion of  
2 tropical Australian savanna to closed forest during the 20th century. *Landscape Ecology*, **21(8)**, 1253-1266.
- 3 Brook, B.W., Sodhi, N.S., and Bradshaw, C.J.A., 2008: Synergies among extinction drivers under global change.  
4 *Trends in Ecology & Evolution*, **23(8)**, 453-460.
- 5 Brouwers, N., Matusick, G., Ruthrof, K., Lyons, T., and Hardy, G., 2013: Landscape-scale assessment of tree crown  
6 dieback following extreme drought and heat in a Mediterranean eucalypt forest ecosystem. *Landscape Ecology*,  
7 **28(1)**, 69-80.
- 8 Brouwers, N.C., Mercer, J., Lyons, T., Poot, P., Veneklaas, E., and Hardy, G., 2012: Climate and landscape drivers  
9 of tree decline in a Mediterranean ecoregion. *Ecology and Evolution*, **3(1)**, 67-79.
- 10 Brown, C.D., 2010: *Tree-line Dynamics: Adding Fire to Climate Change Prediction* pp.
- 11 Brown, L.E., Hannah, D.M., and Milner, A.M., 2007: Vulnerability of alpine stream biodiversity to shrinking  
12 glaciers and snowpacks. *Global Change Biology*, **13(5)**, 958-966.
- 13 Bryant, M.D., 2009: Global climate change and potential effects on Pacific salmonids in freshwater ecosystems of  
14 southeast Alaska. *Climatic Change*, **95(1-2)**, 169-193.
- 15 Buckley, J., Butlin, R.K., and Bridle, J.R., 2012: Evidence for evolutionary change associated with the recent range  
16 expansion of the British butterfly, *Aricia agestis*, in response to climate change. *Molecular Ecology*, **21(2)**, 267-  
17 280.
- 18 Buisson, L., and Grenouillet, G., 2009: Contrasted impacts of climate change on stream fish assemblages along an  
19 environmental gradient. *Diversity and Distributions*, **15(4)**, 613-626.
- 20 Buisson, L., Thuiller, W., Lek, S., Lim, P., and Grenouillet, G., 2008: Climate change hastens the turnover of stream  
21 fish assemblages. *Global Change Biology*, **14(10)**, 2232-2248.
- 22 Buitenwerf, R., Bond, W.J., Stevens, N., and Trollope, W.W., 2012: Increased tree densities in two South African  
23 savannas: > 50 years of data suggests CO<sub>2</sub> as a driver. *Global Change Biology*, **18(2)**, 675-684.
- 24 Bunn, S.E., and Arthington, A.H., 2002: Basic Principles and Ecological Consequences of Altered Flow Regimes  
25 for Aquatic Biodiversity. *Environmental Management*, **30(4)**, 492-507.
- 26 Burgmer, T., Hillebrand, H., and Pfenninger, M., 2007: Effects of climate-driven temperature changes on the  
27 diversity of freshwater macroinvertebrates. *Oecologia*, **151(1)**, 93-103.
- 28 Burkhead, N.M., 2012: Extinction Rates in North American Freshwater Fishes, 1900-2010. *Bioscience*, **62(9)**, 798-  
29 808.
- 30 Burrows, M.T., Schoeman, D.S., Buckley, L.B., Moore, P., Poloczanska, E.S., Brander, K.M., Brown, C., Bruno,  
31 J.F., Duarte, C.M., Halpern, B.S., Holding, J., Kappel, C.V., Kiessling, W., O'Connor, M.I., Pandolfi, J.M.,  
32 Parmesan, C., Schwing, F.B., Sydeman, W.J., and Richardson, A.J., 2011: The Pace of Shifting Climate in  
33 Marine and Terrestrial Ecosystems. *Science*, **334(6056)**, 652-655.
- 34 Burton, O.J., Phillips, B.L., and Travis, J.M.J., 2010: Trade-offs and the evolution of life-histories during range  
35 expansion. *Ecology Letters*, **13(10)**, 1210-1220.
- 36 Buswell, J.M., Moles, A.T., and Hartley, S., 2011: Is rapid evolution common in introduced plant species? *Journal*  
37 *of Ecology*, **99(1)**, 214-224.
- 38 Butt, N., de Oliveira, P.A., and Costa, M.H., 2011: Evidence that deforestation affects the onset of the rainy season  
39 in Rondonia, Brazil. *Journal of Geophysical Research-Atmospheres*, **116(D11120)**, 1-8.
- 40 Cabral, A.C., Miguel, J.M., Rescia, A.J., Schmitz, M.F., and Pineda, F.D., 2009: Shrub encroachment in  
41 Argentinean savannas. *Journal of Vegetation Science*, **14(2)**, 145-152.
- 42 Cadotte, M.W., 2006: Dispersal and species diversity: A meta-analysis. *American Naturalist*, **167(6)**, 913-924.
- 43 Caesar, J., Palin, E., Liddicoat, S., Lowe, J., Burke, E., Pardaens, A., Sanderson, M., and Kahana, R., 2012:  
44 Response of the HadGEM2 Earth System Model to future greenhouse gas emissions pathways. *Journal of*  
45 *Climate*.
- 46 Cahill, A.E., Aiello-Lammens, M.E., Fisher-Reid, M.C., Hua, X., Karanewsky, C.J., Ryu, H.Y., Sbeglia, G.C.,  
47 Spagnolo, F., Waldron, J.B., Warsi, O., and Wiens, J.J., 2013: How does climate change cause extinction?  
48 *Proceedings of the Royal Society B-Biological Sciences*, **280(1750)**.
- 49 Cailleret, M., Nourtier, M., Amm, A., Durand-Gillmann, M., and Davi, H., 2013: Drought-induced decline and  
50 mortality of silver fir differ among three sites in Southern France. *Annals of Forest Science*, 1-15.
- 51 Caissie, D., 2006: The thermal regime of rivers: a review. *Freshwater Biology*, **51(8)**, 1389-1406.
- 52 Caldow, R.W.G., Stillman, R.A., Durell, S.E.A.I.V.d., West, A.D., McGroarty, S., Goss-Custard, J.D., Wood, P.J.,  
53 and Humphreys, J., 2007: Benefits to shorebirds from invasion of a non-native shellfish. *Proceedings of the*  
54 *Royal Society B-Biological Sciences*, **274(1616)**, 1449-1455.

- 1 Cameron, A., 2012: Refining risk estimates using models. In *Saving a Million Species: Extinction Risk from Climate*  
2 *Change* [L. Hannah (ed.)]. Island Press, Washington, Covelo, London, pp. 41-72.
- 3 Canadell, J.G., Le Quéré, C., Raupach, M.R., Field, C.B., Buitenhuis, E.T., Ciais, P., Conway, T.J., Gillett, N.P.,  
4 Houghton, R.A., and Marland, G., 2007: Contributions to accelerating atmospheric CO<sub>2</sub> growth from economic  
5 activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the National Academy of Sciences*,  
6 **104(47)**, 18866-18870.
- 7 Cannone, N., Diolaiuti, G., Guglielmin, M., and Smiraglia, C., 2008: Accelerating climate change impacts on alpine  
8 glacier forefield ecosystems in the European Alps. *Ecological Applications*, **18(3)**, 637-648.
- 9 Cannone, N., Sgorbati, S., and Guglielmin, M., 2007: Unexpected impacts of climate change on alpine vegetation.  
10 *Frontiers in Ecology and the Environment*, **5(7)**, 360-364.
- 11 Capon, S.J., 2007: Effects of flooding on seedling emergence from the soil seed bank of a large desert floodplain.  
12 *Wetlands*, **27(4)**, 904-914.
- 13 Carey, M., French, A., and O'Brien, E., 2011: Unintended effects of technology on climate change adaptation: an  
14 historical analysis of water conflicts below Andean Glaciers. *Journal of Historical Geography*, **38(2012)**, 181-  
15 191.
- 16 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  
17 the coastal Atlantic forest to pasture: Consequences for the nitrogen cycle and soil greenhouse gas emissions.  
18 *Agriculture, Ecosystems & Environment*, **148(0)**, 37-43.
- 19 Carney, K.M., Hungate, B.A., Drake, B.G., and Megonigal, J.P., 2007: Altered soil microbial community at elevated  
20 CO<sub>2</sub> leads to loss of soil carbon. *Proceedings of the National Academy of Sciences of the United States of*  
21 *America*, **104(12)**, 4990-4995.
- 22 Carnicer, J., Coll, M., Ninyerola, M., Pons, X., Sanchez, G., and Penuelas, J., 2011: Widespread crown condition  
23 decline, food web disruption, and amplified tree mortality with increased climate change-type drought.  
24 *Proceedings of the National Academy of Sciences of the United States of America*, **108(4)**, 1474-1478.
- 25 Chapin III, F.S., Sturm, M., Serreze, M.C., McFadden, J.P., Key, J.R., Lloyd, A.H., McGuire, A.D., Rupp, T.S.,  
26 Lynch, A.H., Schimel, J.P., Beringer, J., Chapman, W.L., Epstein, H.E., Euskirchen, E.S., Hinzman, L.D., Jia,  
27 G., Ping, C.L., Tape, K.D., Thompson, C.D.C., Walker, D.A., and Welker, J.M., 2005: Role of land-surface  
28 changes in Arctic summer warming. *Science*, **310(5748)**, 657-660.
- 29 Charru, M., Seynave, I., Morneau, F., and Bontemps, J.D., 2010: Recent changes in forest productivity: An analysis  
30 of national forest inventory data for common beech (*Fagus sylvatica* L.) in north-eastern France. *Forest Ecology*  
31 *and Management*, **260(5)**, 864-874.
- 32 Cheaib, A., Badeau, V., Boe, J., Chuine, I., Delire, C., Dufrêne, E., François, C., Gritti, E.S., Legay, M., Pagé, C.,  
33 Thuiller, W., Viovy, N., and Leadley, P., 2012: Climate change impacts on tree ranges: model intercomparison  
34 facilitates understanding and quantification of uncertainty. *Ecology Letters*, **15(6)**, 533-544.
- 35 Chen, I.-C., Hill, J.K., Ohlemüller, R., Roy, D.B., and Thomas, C.D., 2011: Rapid Range Shifts of Species  
36 Associated with High Levels of Climate Warming. *Science*, **333(6045)**, 1024-1026.
- 37 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:  
38 Elevation increases in moth assemblages over 42 years on a tropical mountain. *Proceedings of the National*  
39 *Academy of Sciences of the United States of America*, **106(5)**, 1479-1483.
- 40 Chessman, B.C., 2009: Climatic changes and 13-year trends in stream macroinvertebrate assemblages in New South  
41 Wales, Australia. *Global Change Biology*, **15(11)**, 2791-2802.
- 42 Chevin, L.M., Lande, R., and Mace, G.M., 2010: Adaptation, Plasticity, and Extinction in a Changing Environment:  
43 Towards a Predictive Theory. *Plos Biology*, **8(4)**.
- 44 Chiba, S., and Roy, K., 2011: Selectivity of terrestrial gastropod extinctions on an oceanic archipelago and insights  
45 into the anthropogenic extinction process. *Proceedings of the National Academy of Sciences of the United States*  
46 *of America*, **108(23)**, 9496-9501.
- 47 Chisholm, R.A., 2010: Trade-offs between ecosystem services: Water and carbon in a biodiversity hotspot.  
48 *Ecological Economics*, **69(10)**, 1973-1987.
- 49 Chmura, D.J., Anderson, P.D., Howe, G.T., Harrington, C.A., Halofsky, J.E., Peterson, D.L., Shaw, D.C., and St  
50 Clair, J.B., 2011: Forest responses to climate change in the northwestern United States: Ecophysiological  
51 foundations for adaptive management. *Forest Ecology and Management*, **261(7)**, 1121-1142.
- 52 Choat, B., Jansen, S., Brodribb, T.J., Cochard, H., Delzon, S., Bhaskar, R., Bucci, S.J., Feild, T.S., Gleason, S.M.,  
53 Hacke, U.G., Jacobsen, A.L., Lens, F., Maherali, H., Martinez-Vilalta, J., Mayr, S., Mencuccini, M., Mitchell,

- 1 P.J., Nardini, A., Pittermann, J., Pratt, R.B., Sperry, J.S., Westoby, M., Wright, I.J., and Zanne, A.E., 2012:  
2 Global convergence in the vulnerability of forests to drought. *Nature*, **491(7426)**, 752-+.
- 3 Chown, S.L., Hoffmann, A.A., Kristensen, T.N., Angilletta, M.J., Stenseth, N.C., and Pertoldi, C., 2010: Adapting  
4 to climate change: a perspective from evolutionary physiology. *Climate Research*, **43(1-2)**, 3-15.
- 5 Chown, S.L., Huiskes, A.H.L., Gremmen, N.J.M., Lee, J.E., Terauds, A., Crosbie, K., Frenot, Y., Hughes, K.A.,  
6 Imura, S., Kiefer, K., Lebouvier, M., Raymond, B., Tsujimoto, M., Ware, C., van den Vijver, B., and  
7 Bergstrom, D.M., 2012: Continent-wide risk assessment for the establishment of nonindigenous species in  
8 Antarctica. *Proceedings of the National Academy of Sciences of the United States of America*, **109(13)**, 4938-  
9 4943.
- 10 Christie, P., and Sommerkorn, M., 2012: *RaCeR: Rapid assessment of Circum-arctic ecosystem Resilience* WWF  
11 Global arctic programme, Ottawa, Canada, 72-72 pp.
- 12 Chuine, I., Morin, X., Sonie, L., Collin, C., Fabreguettes, J., Degueldre, D., Salager, J.L., and Roy, J., 2012: Climate  
13 change might increase the invasion potential of the alien C4 grass *Setaria parviflora* (Poaceae) in the  
14 Mediterranean Basin. *Diversity and Distributions*, **18(7)**, 661-672.
- 15 Churkina, G., Zaehle, S., Hughes, J., Viogy, N., Chen, Y., Jung, M., Heumann, B.W., Ramankutty, N., Heimann,  
16 M., and Jones, C., 2010: Interactions between nitrogen deposition, land cover conversion, and climate change  
17 determine the contemporary carbon balance of Europe. *Biogeosciences*, **7(9)**, 2749-2764.
- 18 Ciais, P., Reichstein, M., Viogy, N., Granier, A., Ogee, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C.,  
19 Carrara, A., Chevallier, F., De Noblet, N., Friend, A.D., Friedlingstein, P., Grunwald, T., Heinesch, B.,  
20 Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M.,  
21 Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T., and  
22 Valentini, R., 2005: Europe-wide reduction in primary productivity caused by the heat and drought in 2003.  
23 *Nature*, **437(7058)**, 529-533.
- 24 Ciais, P., Sabine, C., and others, in press: Carbon and Biogeochemical Cycles. In *Contribution of Working Group 1*  
25 *to the 5th Assessment Report of the Intergovernmental Panel on Climate Change* [T. F. Stocker (ed.)]. pp.
- 26 Ciais, P., Schelhaas, M.J., Zaehle, S., Piao, L., Cescatti, A., Liski, J., Luyssaert, S., Le-Maire, G., Schulze, E.D.,  
27 Bouriaud, O., Freibauer, A., Valentini, R., and Nabuurs, G.J., 2008: Carbon accumulation in European forests.  
28 *Nature Geoscience*, **1(7)**, 425-429.
- 29 Clark, D.A., Piper, S.C., Keeling, C.D., and Clark, D.B., 2003: Tropical rain forest tree growth and atmospheric  
30 carbon dynamics linked to interannual temperature variation during 1984-2000. *Proceedings of the National*  
31 *Academy of Sciences of the United States of America*, **100(10)**, 5852-5857.
- 32 Clark, J.S., 1998: Why trees migrate so fast: Confronting theory with dispersal biology and the paleorecord.  
33 *American Naturalist*, **152(2)**, 204-224.
- 34 Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., and  
35 McCabe, A.M., 2009: The Last Glacial Maximum. *Science*, **325(5941)**, 710-714.
- 36 Clarke, A., and Rothery, P., 2008: Scaling of body temperature in mammals and birds. *Functional Ecology*, **22**, 58-  
37 67.
- 38 Claussen, M., 2009: Late Quaternary vegetation-climate feedbacks. *Climate of the Past*, **5(2)**, 203-216.
- 39 Clavero, M., Villero, D., and Brotons, L., 2011: Climate change or land use dynamics: Do we know what climate  
40 change indicators indicate? *PLoS One*, **6(4)**, e18581.
- 41 Cleland, E., and Harpole, W.S., 2010: Nitrogen enrichment and plant communities. *Annals of the New York*  
42 *Academy of Sciences*, **1195(1)**, 46-61.
- 43 Cleland, E.E., Allen, J.M., Crimmins, T.M., Dunne, J.A., Pau, S., Travers, S., Zavaleta, E.S., and Wolkovich, E.M.,  
44 2012: Phenological tracking enables positive species responses to climate change. *Ecology*, **93(8)**, 1765-1771.
- 45 Cleland, E.E., Chuine, I., Menzel, A., Mooney, H.A., and Schwartz, M.D., 2007: Shifting plant phenology in  
46 response to global change. *Trends in Ecology & Evolution*, **22(7)**, 357-365.
- 47 Clements, D.R., and Ditommaso, A., 2011: Climate change and weed adaptation: can evolution of invasive plants  
48 lead to greater range expansion than forecasted? *Weed Research*, **51(3)**, 227-240.
- 49 Cobben, M.M.P., Verboom, J., Opdam, P.F.M., Hoekstra, R.F., Jochem, R., and Smulders, M.J.M., 2012: Wrong  
50 place, wrong time: climate change-induced range shift across fragmented habitat causes maladaptation and  
51 declined population size in a modelled bird species. *Global Change Biology*, **18(8)**, 2419-2428.
- 52 Cochrane, M.A., 2003: Fire science for rainforests. *Nature*, **421**, 913-919.
- 53 Cochrane, M.A., and Barber, C.P., 2009: Climate change, human land use and future fires in the Amazon. *Global*  
54 *Change Biology*, **15(3)**, 601-612.

- 1 Colautti, R.I., Eckert, C.G., and Barrett, S.C.H., 2010: Evolutionary constraints on adaptive evolution during range  
2 expansion in an invasive plant. *Proceedings of the Royal Society B-Biological Sciences*, **277(1689)**, 1799-1806.
- 3 Collatz, M.H., Ribbas-Carbo, M., and Berry, J.A., 1992: Coupled photosynthesis-stomatal conductances model for  
4 leaves of C4 plants. *Australian Journal of Plant Physiology*, **19**, 519-538.
- 5 Collins, J.P., 2010: Amphibian decline and extinction: What we know and what we need to learn. *Diseases of*  
6 *Aquatic Organisms*, **92(2-3)**, 93-99.
- 7 Collins, W.J., Sitch, S., and Boucher, O., 2010: How vegetation impacts affect climate metrics for ozone precursors.  
8 *Journal of Geophysical Research-Atmospheres*, **115(D23308)**, 1-14.
- 9 Colls, A., Ash, N., and Ikkala, N., 2009: *Ecosystem-based Adaptation: a natural response to climate change*. Gland,  
10 Switzerland, 16 pp.
- 11 Colwell, R.K., Brehm, G., Cardelus, C.L., Gilman, A.C., and Longino, J.T., 2008: Global warming, elevational  
12 range shifts, and lowland biotic attrition in the wet tropics. *Science*, **322(5899)**, 258-261.
- 13 Conlisk, E., Lawson, D., Syphard, A.D., Franklin, J., Flint, L., Flint, A., and Regan, H.M., 2012: The Roles of  
14 Dispersal, Fecundity, and Predation in the Population Persistence of an Oak (*Quercus engelmannii*) under  
15 Global Change. *Plos One*, **7(5)**.
- 16 Connell, J.H., 1978: Diversity in tropical rain forests and coral reefs. *Science*, **199**, 1302-1310.
- 17 Cook, B.I., Cook, E.R., Huth, P.C., Thompson, J.E., Forster, A., and Smiley, D., 2008: A cross-taxa phenological  
18 dataset from Mohonk Lake, NY and its relationship to climate. *International Journal of Climatology*, **28(10)**,  
19 1369-1383.
- 20 Cook, B.I., Wolkovich, E.M., and Parmesan, C., 2012: Divergent responses to spring and winter warming drive  
21 community level flowering trends. *Proceedings of the National Academy of Sciences of the United States of*  
22 *America*, **(in press)**.
- 23 Cooper, O.R., Parrish, D.D., Stohl, A., Trainer, M., Nedelec, P., Thouret, V., Cammas, J.P., Oltmans, S.J., Johnson,  
24 B.J., Tarasick, D., Leblanc, T., McDermid, I.S., Jaffe, D., Gao, R., Stith, S., Ryerson, T., Aikin, K., Campos, T.,  
25 Weinheimer, A., and Avery, A.M., 2010: Increasing springtime ozone mixing ratios in the free troposphere over  
26 western North America. *Nature*, **463(12)**, 344-348.
- 27 Coppack, T., and Both, C., 2002: Predicting life-cycle adaptation of migratory birds to global climate change.  
28 *Ardea*, **90(3)**, 369-378.
- 29 Corlett, R.T., 2011: Impacts of warming on tropical lowland rainforests. *Trends in Ecology & Evolution*, **26(11)**,  
30 606-613.
- 31 Costa, M.H., Yanagi, S.N.M., Souza, P., Ribeiro, A., and Rocha, E.J.P., 2007: Climate change in Amazonia caused  
32 by soybean cropland expansion, as compared to caused by pastureland expansion. *Geophysical Research*  
33 *Letters*, **34(7)**.
- 34 Cox, P.M., Betts, R.A., Jones, C.D., Spall, S.A., and Totterdell, I.J., 2000: Acceleration of global warming due to  
35 carbon-cycle feedbacks in a coupled climate model. *Nature*, **408(6809)**, 184-187.
- 36 Cox, P.M., Huntingford, C., and Harding, R.J., 1998: A canopy conductance and photosynthesis model for use in a  
37 GCM land surface scheme. *Journal of Hydrology*, **212-213**, 79-94.
- 38 Cox, P.M., Pearson, D., Booth, B.B., Friedlingstein, P., Huntingford, C., Jones, C.D., and Luke, C.M., 2013:  
39 Sensitivity of tropical carbon to climate change constrained by carbon dioxide variability. *Nature*, **advance**  
40 **online publication**.
- 41 Crimmins, S.M., Dobrowski, S.Z., Greenberg, J.A., Abatzoglou, J.T., and Mynsberge, A.R., 2011: Changes in  
42 Climatic Water Balance Drive Downhill Shifts in Plant Species' Optimum Elevations. *Science*, **331(6015)**, 324-  
43 327.
- 44 Crimmins, T.M., Crimmins, M.A., and Bertelsen, C.D., 2009: Flowering range changes across an elevation gradient  
45 in response to warming summer temperatures. *Global Change Biology*, **15(5)**, 1141-1152.
- 46 Crous, C.J., Jacobs, S.M., and Esler, K.J., 2012: Drought-tolerance of an invasive alien tree, *Acacia mearnsii* and  
47 two native competitors in fynbos riparian ecotones. *Biological Invasions*, **14(3)**, 619-631.
- 48 Cui, X.F., and Graf, H.F., 2009: Recent land cover changes on the Tibetan Plateau: a review. *Climatic Change*,  
49 **94(1-2)**, 47-61.
- 50 Cullen, L.E., Stewart, G.H., Duncan, R.P., and Palmer, J.G., 2001: Disturbance and climate warming influences on  
51 New Zealand Nothofagus tree-line population dynamics. *Journal of Ecology*, **89(6)**, 1061-1071.
- 52 Curran, L.M., Trigg, S.N., McDonald, A.K., Astiani, D., Hardiono, Y.M., Siregar, P., Caniago, I., and Kasischke, E.,  
53 2004: Lowland forest loss in protected areas of Indonesian Borneo. *Science*, **303(5660)**, 1000-1003.

- 1 da Costa, A.C.L., Galbraith, D., Almeida, S., Portela, B.T.T., Da Costa, M., De Athaydes Silva Junior, J., Braga,  
2 A.P., De Gonçalves, P.H.L., De Oliveira, A.A., Fisher, R., Phillips, O.L., Metcalfe, D.B., Levy, P., and Meir,  
3 P., 2010: Effect of 7 yr of experimental drought on vegetation dynamics and biomass storage of an eastern  
4 Amazonian rainforest. *New Phytologist*, **187(3)**, 579-591.
- 5 Dahm, C.N., Baker, M.A., Moore, D.I., and Thibault, J.R., 2003: Coupled biogeochemical and hydrological  
6 responses of streams and rivers to drought. *Freshwater Biology*, **48(7)**, 1219-1231.
- 7 Dai, F., Su, Z., Liu, S., and Liu, G., 2011: Temporal variation of soil organic matter content and potential  
8 determinants in Tibet, China. *Catena*, **85(3)**, 288-294.
- 9 Dale, V.H., Tharp, M.L., Lannom, K.O., and Hodges, D.G., 2010: Modeling transient response of forests to climate  
10 change. *Science of the Total Environment*, **408(8)**, 1888-1901.
- 11 Danby, R.K., and Hik, D.S., 2007: Variability, contingency and rapid change in recent subarctic alpine tree line  
12 dynamics. *Journal of Ecology*, **95(2)**, 352-363.
- 13 Daniau, A.L., Bartlein, P.J., Harrison, S.P., Prentice, I.C., Brewer, S., Friedlingstein, P., Harrison-Prentice, T.I.,  
14 Inoue, J., Izumi, K., Marlon, J.R., Mooney, S., Power, M.J., Stevenson, J., Tinner, W., Andric, M., Atanassova,  
15 J., Behling, H., Black, M., Blarquez, O., Brown, K.J., Carcaillet, C., Colhoun, E.A., Colombaroli, D., Davis,  
16 B.A.S., D'Costa, D., Dodson, J., Dupont, L., Eshetu, Z., Gavin, D.G., Genries, A., Haberle, S., Hallett, D.J.,  
17 Hope, G., Horn, S.P., Kassa, T.G., Katamura, F., Kennedy, L.M., Kershaw, P., Krivonogov, S., Long, C.,  
18 Magri, D., Marinova, E., McKenzie, G.M., Moreno, P.I., Moss, P., Neumann, F.H., Norstrom, E., Paitre, C.,  
19 Rius, D., Roberts, N., Robinson, G.S., Sasaki, N., Scott, L., Takahara, H., Terwilliger, V., Thevenon, F., Turner,  
20 R., Valsecchi, V.G., Vanniere, B., Walsh, M., Williams, N., and Zhang, Y., 2012: Predictability of biomass  
21 burning in response to climate changes. *Global Biogeochemical Cycles*, **26(GB4007)**,  
22 **doi:10.1029/2011GB004249**.
- 23 Daniau, A.L., Harrison, S.P., and Bartlein, P.J., 2010: Fire regimes during the Last Glacial. *Quaternary Science*  
24 *Reviews*, **29(21-22)**, 2918-2930.
- 25 Daufresne, M., and Boet, P., 2007: Climate change impacts on structure and diversity of fish communities in rivers.  
26 *Global Change Biology*, **13(12)**, 2467-2478.
- 27 Davidson, A.M., Jennions, M., and Nicotra, A.B., 2011: Do invasive species show higher phenotypic plasticity than  
28 native species and, if so, is it adaptive? A meta-analysis. *Ecology Letters*, **14(4)**, 419-431.
- 29 Davidson, E.A., and Janssens, I.A., 2006: Temperature sensitivity of soil carbon decomposition and feedbacks to  
30 climate change. *Nature*, **440**, 165-173.
- 31 Davies, T.J., Smith, G.F., Bellstedt, D.U., Boatwright, J.S., Bytebier, B., Cowling, R.M., Forest, F., Harmon, L.J.,  
32 Muasya, A.M., Schrire, B.D., Steenkamp, Y., van der Bank, M., and Savolainen, V., 2011: Extinction Risk and  
33 Diversification Are Linked in a Plant Biodiversity Hotspot. *Plos Biology*, **9(5)**.
- 34 Davin, E.L., and de Noblet-Ducoudre, N., 2010: Climatic Impact of Global-Scale Deforestation: Radiative versus  
35 Nonradiative Processes. *Journal of Climate*, **23(1)**, 97-112.
- 36 Davin, E.L., de Noblet-Ducoudre, N., and Friedlingstein, P., 2007: Impact of land cover change on surface climate:  
37 Relevance of the radiative forcing concept. *Geophysical Research Letters*, **34(13)**.
- 38 Davis, C.C., Willis, C.G., Primack, R.B., and Miller-Rushing, A.J., 2010: The importance of phylogeny to the study  
39 of phenological response to global climate change. *Philosophical Transactions of the Royal Society B-*  
40 *Biological Sciences*, **365(1555)**, 3201-3213.
- 41 Davis, J.L., S., and Thompson, R., 2010: Freshwater biodiversity and climate change. In *Managing climate change:*  
42 *papers from the Greenhouse 2009 conference* [I. Jubb, P. Holper & W. Cai (eds.)]. CSIRO Publishing,  
43 Collingwood, Australia, pp. 73-84.
- 44 Dawes, M.A., Hättenschwiler, S., Bebi, P., Hagedorn, F., Handa, I.T., Körner, C., and Rixen, C., 2011: Species-  
45 specific tree growth responses to 9 years of CO2 enrichment at the alpine treeline. *Journal of Ecology*, **99(2)**,  
46 383-394.
- 47 Dawson, T.P., Jackson, S.T., House, J.I., Prentice, I.C., and Mace, G.M., 2011: Beyond Predictions: Biodiversity  
48 Conservation in a Changing Climate. *Science*, **332(6025)**, 53-58.
- 49 de Jong, R., de Bruin, S., de Wit, A., Schaepman, M.E., and Dent, D.L., 2011: Analysis of monotonic greening and  
50 browning trends from global NDVI time-series. *Remote Sensing of Environment*, **115(2)**, 692-702.
- 51 De Kauwe, M.G., Medlyn, B.E., Zaehle, S., Walker, A.P., Dietze, M.C., Hickler, T., Jain, A.K., Luo, Y., Parton,  
52 W.J., Prentice, C., Smith, B., Thornton, P.E., Wang, S., Wang, Y.-P., Wårlind, D., Weng, E.S., Crous, K.Y.,  
53 Ellsworth, D.S., Hanson, P.J., Seok-Kim, H., Warren, J.M., Oren, R., and Norby, R.J., 2013: Forest water use

- 1 and water use efficiency at elevated CO<sub>2</sub>: a model-data intercomparison at two contrasting temperate forest  
2 FACE sites. *Global Change Biology*, in press.
- 3 de Vries, W., and Posch, M., 2011: Modelling the impact of nitrogen deposition, climate change and nutrient  
4 limitations on tree carbon sequestration in Europe for the period 1900-2050. *Environmental Pollution*, **159(10)**,  
5 2289-2299.
- 6 DeFries, R.S., Rudel, T., Uriarte, M., and Hansen, M., 2010: Deforestation driven by urban population growth and  
7 agricultural trade in the twenty-first century. *Nature Geoscience*, **3(3)**, 178-181.
- 8 Delire, C., de Noblet-Ducoudre, N., Sima, A., and Gouirand, I., 2011: Vegetation Dynamics Enhancing Long-Term  
9 Climate Variability Confirmed by Two Models. *Journal of Climate*, **24(9)**, 2238-2257.
- 10 DeMichele, C., Accatino, F., Vezzoli, R., and Scholes, R.J., 2011: Savanna domain in the herbivores-fire parameter  
11 space exploiting a tree-grass-soil water dynamic model. *Journal of Theoretical Biology*, **289**, 74-82.
- 12 Denman, K.L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P.M., Dickinson, R.E., Hauglustaine, D., Heinze, C.,  
13 Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., da Silva Dias, P.L., Wofsy, S.C., and Zhang, X., 2007:  
14 Couplings Between Changes in the Climate System and Biogeochemistry. In *Climate Change 2007: The*  
15 *Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the*  
16 *Intergovernmental Panel on Climate Change* [S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B.  
17 Averyt, M. Tignor & H. L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New  
18 York, NY, USA., pp.
- 19 Dentener, F., Keating, T., and Akimoto, H., 2010: *Hemispheric Transport of Air Pollution part A: Ozone and*  
20 *Particulate Matter*. UNECE Air Pollution Series Series 17, 304 pp.
- 21 DeRose, R.J., and Long, J.N., 2012: Drought-driven disturbance history characterizes a southern Rocky Mountain  
22 subalpine forest. *Canadian Journal of Forest Research*, **42(9)**, 1649-1660.
- 23 Deutsch, C.A., Tewksbury, J.J., Huey, R.B., Sheldon, K.S., Ghalambor, C.K., Haak, D.C., and Martin, P.R., 2008:  
24 Impacts of climate warming on terrestrial ectotherms across latitude. *Proceedings of the National Academy of*  
25 *Sciences*, **105(18)**, 6668-6672.
- 26 Devi, N., Hagedorn, F., Moiseev, P., Bugmann, H., Shiyatov, S., Mazepa, V., and Rigling, A., 2008: Expanding  
27 forests and changing growth forms of Siberian larch at the Polar Urals treeline during the 20th century. *Global*  
28 *Change Biology*, **14(7)**, 1581-1591.
- 29 Devictor, V., van Swaay, C., Brereton, T., Brotons, L., Chamberlain, D., Heliola, J., Herrando, S., Julliard, R.,  
30 Kuussaari, M., Lindstrom, A., Reif, J., Roy, D.B., Schweiger, O., Settele, J., Stefanescu, C., Van Strien, A., Van  
31 Turnhout, C., Vermouzek, Z., WallisDeVries, M., Wynhoff, I., and Jiguet, F., 2012: Differences in the climatic  
32 debts of birds and butterflies at a continental scale. *Nature Climate Change*, **2(2)**, 121-124.
- 33 Dial, R.J., Berg, E.E., Timm, K., McMahon, A., and Geck, J., 2007: Changes in the alpine forest-tundra ecotone  
34 commensurate with recent warming in southcentral Alaska: Evidence from orthophotos and field plots. *J.*  
35 *Geophys. Res.*, **112(G4)**, G04015.
- 36 Dieleman, W.I.J., Vicca, S., Dijkstra, F.A., Hagedorn, F., Hovenden, M.J., Larsen, K.S., Morgan, J.A., Volder, A.,  
37 Beier, C., Dukes, J.S., King, J., Leuzinger, S., Linder, S., Luo, Y., Oren, R., De Angelis, P., Tingey, D.,  
38 Hoosbeek, M.R., and Janssens, I.A., 2012: Simple additive effects are rare: a quantitative review of plant  
39 biomass and soil process responses to combined manipulations of CO<sub>2</sub> and temperature. *Global Change*  
40 *Biology*, **18(9)**, 2681-2693.
- 41 Diez, J.M., D'Antonio, C.M., Dukes, J.S., Grosholz, E.D., Olden, J.D., Sorte, C.J.B., Blumenthal, D.M., Bradley,  
42 B.A., Early, R., Ibanez, I., Jones, S.J., Lawler, J.J., and Miller, L.P., 2012: Will extreme climatic events  
43 facilitate biological invasions? *Frontiers in Ecology and the Environment*, **10(5)**, 249-257.
- 44 Diffenbaugh, N.S., and Giorgi, F., 2012: Climate change hotspots in the CMIP5 global climate model ensemble.  
45 *Climatic Change*, **114(3-4)**, 813-822.
- 46 Diffenbaugh, N.S., Pal, J.S., Trapp, R.J., and Giorgi, F., 2005: Fine-scale processes regulate the response of extreme  
47 events to global climate change. *Proceedings of the National Academy of Sciences of the United States of*  
48 *America*, **102(44)**, 15774-15778.
- 49 Dise, N.B., 2009: Peatland Response to Global Change. *Science*, **326(5954)**, 810-811.
- 50 Doak, D.F., and Morris, W.F., 2010: Demographic compensation and tipping points in climate-induced range shifts.  
51 *Nature*, **467(7318)**, 959-962.
- 52 Dobrowski, S.Z., Abatzoglou, J., Swanson, A.K., Greenberg, J.A., Mynsberge, A.R., Holden, Z.A., and Schwartz,  
53 M.K., 2013: The climate velocity of the contiguous United States during the 20th century. *Global Change*  
54 *Biology*, **19(1)**, 241-251.



- 1 Dohrenbusch, A., and Bolte, A., 2007: Forest plantations. In *Wood production, wood technology and*  
2 *biotechnological impacts*. [U. Kües (ed.)]. Universitätsverlag Göttingen, Göttingen, Germany, pp. 73-83.
- 3 Donnelly, A., Caffarra, A., Kelleher, C.T., O'Neill, B.F., Diskin, E., Pletsers, A., Proctor, H., Stirnemann, R.,  
4 O'Halloran, J., Penuelas, J., Hodkinson, T.R., and Sparks, T.H., 2012: Surviving in a warmer world:  
5 environmental and genetic responses. *Climate Research*, **53(3)**, 245-262.
- 6 Doughty, C.E., Field, C.B., and McMillan, A.M.S., 2011: Can crop albedo be increased through modification of leaf  
7 trichomes, and could this cool the regional climate? *Climatic Change*, **104(2)**, 379-387.
- 8 Doughty, C.E., and Goulden, M.L., 2008: Are tropical forests near a high temperature threshold? *Journal of*  
9 *Geophysical Research-Biogeosciences*, **113**.
- 10 Doxford, S.W., and Freckleton, R.P., 2012: Changes in the large-scale distribution of plants: extinction, colonisation  
11 and the effects of climate. *Journal of Ecology*, **100(2)**, 519-529.
- 12 Drake, J.E., Gallet-Budynek, A., Hofmockel, K.S., Bernhardt, E.S., Billings, S.A., Jackson, R.B., Johnsen, K.S.,  
13 Lichter, J., McCarthy, H.R., McCormack, M.L., Moore, D.J.P., Oren, R., Palmroth, S., Phillips, R.P., Phippen,  
14 J.S., Pritchard, S.G., Treseder, K.K., Schlesinger, W.H., DeLucia, E.H., and Finzi, A.C., 2011: Increases in the  
15 flux of carbon belowground stimulate nitrogen uptake and sustain the long-term enhancement of forest  
16 productivity under elevated CO<sub>2</sub>. *Ecology Letters*, **14(4)**, 349-357.
- 17 Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.I., Knowler, D.J., Leveque, C., Naiman, R.J., Prieur-  
18 Richard, A.H., Soto, D., Stiassny, M.L.J., and Sullivan, C.A., 2006: Freshwater biodiversity: importance,  
19 threats, status and conservation challenges. *Biological Reviews*, **81(2)**, 163-182.
- 20 Dukes, J.S., Pontius, J., Orwig, D., Garnas, J.R., Rodgers, V.L., Brazee, N., Cooke, B., Theoharides, K.A., Stange,  
21 E.E., Harrington, R., Ehrenfeld, J., Gurevitch, J., Lerda, M., Stinson, K., Wick, R., and Ayres, M., 2009:  
22 Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern  
23 North America: What can we predict? *Canadian Journal of Forest Research-Revue Canadienne De Recherche*  
24 *Forestiere*, **39(2)**, 231-248.
- 25 Dulamsuren, C., Hauck, M., Nyambayar, S., Bader, M., Osokhjargal, D., Oyungerel, S., and Leuschner, C., 2009:  
26 Performance of Siberian elm (*Ulmus pumila*) on steppe slopes of the northern Mongolian mountain taiga:  
27 Drought stress and herbivory in mature trees. *Environmental and Experimental Botany*, **66(1)**, 18-24.
- 28 Dullinger, S., Gattringer, A., Thuiller, W., Moser, D., Zimmermann, N.E., Guisan, A., Willner, W., Plutzer, C.,  
29 Leitner, M., Mang, T., Caccianiga, M., Dirnbock, T., Ertl, S., Fischer, A., Lenoir, J., Svenning, J.C., Psomas,  
30 A., Schmatz, D.R., Silc, U., Vittoz, P., and Hulber, K., 2012: Extinction debt of high-mountain plants under  
31 twenty-first-century climate change. *Nature Climate Change*, **2(8)**, 619-622.
- 32 Dunn, R.R., Harris, N.C., Colwell, R.K., Koh, L.P., and Sodhi, N.S., 2009: The sixth mass coextinction: are most  
33 endangered species parasites and mutualists? *Proceedings of the Royal Society B-Biological Sciences*,  
34 **276(1670)**, 3037-3045.
- 35 Duquesnay, A., Breda, N., Stievenard, M., and Dupouey, J.L., 1998: Changes of tree-ring delta C-13 and water use  
36 efficiency of beech (*Fagus sylvatica* L.) in north-eastern France during the past century. *Plant Cell and*  
37 *Environment*, **21**, 565-572.
- 38 Durance, I., and Ormerod, S.J., 2007: Climate change effects on upland stream macroinvertebrates over a 25-year  
39 period. *Global Change Biology*, **13(5)**, 942-957.
- 40 Eamus, D., and Palmer, A.R., 2008: Is climate change a possible explanation for woody thickening in arid and semi-  
41 arid regions? *International Journal of Ecology*, **2007**.
- 42 Eastaugh, C.S., Potzelsberger, E., and Hasenauer, H., 2011: Assessing the impacts of climate change and nitrogen  
43 deposition on Norway spruce (*Picea abies* L. Karst) growth in Austria with BIOME-BGC. *Tree Physiology*,  
44 **31(3)**, 262-274.
- 45 Edburg, S.L., Hicke, J.A., Brooks, P.D., Pendall, E.G., Ewers, B.E., Norton, U., Gochis, D., Gutmann, E.D., and  
46 Meddens, A.J.H., 2012: Cascading impacts of bark beetle-caused tree mortality on coupled biogeophysical and  
47 biogeochemical processes. *Frontiers in Ecology and the Environment*, **10(8)**, 416-424.
- 48 Eggermont, H., Verschuren, D., Audenaert, L., Lens, L., Russell, J., Klaassen, G., and Heiri, O., 2010: Limnological  
49 and ecological sensitivity of Rwenzori mountain lakes to climate warming. *Hydrobiologia*, **648(1)**, 123-142.
- 50 Eisenhauer, N., Cesarz, S., Koller, R., Worm, K., and Reich, P.B., 2012: Global change belowground: impacts of  
51 elevated CO<sub>2</sub>, nitrogen, and summer drought on soil food webs and biodiversity. *Global Change Biology*,  
52 **18(2)**, 435-447.
- 53 Eliseev, A.V., and Mokhov, I.I., 2011: Effect of including land-use driven radiative forcing of the surface albedo of  
54 land on climate response in the 16th-21st centuries. *Izvestiya Atmospheric and Oceanic Physics*, **47(1)**, 15-30.

- 1 Ellery, W.N., Scholes, R.J., and Mentis, M.T., 1991: An initial approach to predicting the sensitivity of the South  
2 African grassland biome to climate change. *South African Journal of Science*, **87**, 499-503.
- 3 Elmendorf, S.C., Henry, G.H.R., Hollister, R.D., Bjork, R.G., Boulanger-Lapointe, N., Cooper, E.J., Cornelissen,  
4 J.H.C., Day, T.A., Dorrepaal, E., Elumeeva, T.G., Gill, M., Gould, W.A., Harte, J., Hik, D.S., Hofgaard, A.,  
5 Johnson, D.R., Johnstone, J.F., Jonsdottir, I.S., Jorgenson, J.C., Klanderud, K., Klein, J.A., Koh, S., Kudo, G.,  
6 Lara, M., Levesque, E., Magnusson, B., May, J.L., Mercado-Diaz, J.A., Michelsen, A., Molau, U., Myers-  
7 Smith, I.H., Oberbauer, S.F., Onipchenko, V.G., Rixen, C., Martin Schmidt, N., Shaver, G.R., Spasojevic, M.J.,  
8 orhallsdottir, o.E., Tolvanen, A., Troxler, T., Tweedie, C.E., Villareal, S., Wahren, C.-H., Walker, X., Webber,  
9 P.J., Welker, J.M., and Wipf, S., 2012: Plot-scale evidence of tundra vegetation change and links to recent  
10 summer warming. *Nature Clim. Change*, **advance online publication**.
- 11 Elser, J.J., Andersen, T., Baron, J.S., Bergström, A.K., Jansson, M., Kyle, M., Nydick, K.R., Steger, L., and Hessen,  
12 D.O., 2009: Shifts in Lake N:P Stoichiometry and Nutrient Limitation Driven by Atmospheric Nitrogen  
13 Deposition. *Science*, **326(5954)**, 835-837.
- 14 Elser, J.J., Bracken, M.E.S., Cleland, E.E., Gruner, D.S., Harpole, W.S., Hillebrand, H., Ngai, J.T., Seabloom, E.W.,  
15 Shurin, J.B., and Smith, J.E., 2007: Global analysis of nitrogen and phosphorus limitation of primary producers  
16 in freshwater, marine and terrestrial ecosystems. *Ecology Letters*, **10**, 1135-1142.
- 17 Emmett, B.A., Beier, C., Estiarte, M., Tietema, A., Kristensen, H.L., Williams, D., Penuelas, J., Schmidt, I., and  
18 Sowerby, A., 2004: The response of soil processes to climate change: Results from manipulation studies of  
19 shrublands across an environmental gradient. *Ecosystems*, **7(6)**, 625-637.
- 20 Engler, R., Randin, C.F., Thuiller, W., Dullinger, S., Simmermann, N.E., Araujo, M.B., Pearman, P.B., Le Lay, G.,  
21 Peidallu, C., Albert, C.H., Choler, P., Coldea, G., De Lamo, S., Dirnbock, T., Gegout, J.C., Gomez-Garcia, D.,  
22 Grytnes, J.A., Heegaard, E., Hoistad, F., Nogues-Bravo, D., Normand, S., Puscas, M., Sebastia, M.T., Stanisci,  
23 A., Theurillat, J.P., Trivedi, M.R., Vittoz, P., and Guisan, A., 2011: 21st century climate change threatens  
24 mountain flora unequally across Europe. *Global Change Biology*, **17(7)**, 2330-2341.
- 25 Enquist, B.J., and Enquist, C.A.F., 2011: Long-term change within a Neotropical forest: assessing differential  
26 functional and floristic responses to disturbance and drought. *Global Change Biology*, **17(3)**, 1408-1424.
- 27 Epstein, H., Kaplan, J., Lischke, H., and Yu, Q., 2007: Simulating future changes in arctic tundra and sub-arctic  
28 vegetation. *Computing in Science and Engineering*, **9**, 12-23.
- 29 Epstein, H.E., D. A. Walker, M. K. Reynolds, G. J. Jia, and A. M. Kelley, 2008: Phytomass patterns across a  
30 temperature gradient of the North American arctic tundra. *Journal of Geophysical Research*, **113**.
- 31 Erisman, J.W., Galloway, J., Seitzinger, S., Bleeker, A., and Butterbach-Bahl, K., 2011: Reactive nitrogen in the  
32 environment and its effect on climate change. *Current Opinion in Environmental Sustainability*, **3(5)**, 281-290.
- 33 Erskine, P.D., Lamb, D., and Bristow, M., 2006: Tree species diversity and ecosystem function: Can tropical multi-  
34 species plantations generate greater productivity? *Forest Ecology and Management*, **233(2-3)**, 205-210.
- 35 Essl, F., Dullinger, S., Moser, D., Rabitsch, W., and Kleinbauer, I., 2012: Vulnerability of mires under climate  
36 change: implications for nature conservation and climate change adaptation. *Biodiversity and Conservation*,  
37 **21(3)**, 655-669.
- 38 EU Council, 1992: *Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild*  
39 *fauna and flora*. 66 pp.
- 40 Euskirchen, E.S., McGuire, A.D., Chapin III, F.S., Yi, S., and Thompson, C.C., 2009: Changes in vegetation in  
41 northern Alaska under scenarios of climate change, 2003-2100: implications for climate feedbacks. *Ecological*  
42 *Applications*, **19(4)**, 1022-1043.
- 43 Eycott, A.E., Stewart, G.B., Buyung-Ali, L.M., Bowler, D.E., Watts, K., and Pullin, A.S., 2012: A meta-analysis on  
44 the impact of different matrix structures on species movement rates. *Landscape Ecology*, **27(9)**, 1263-1278.
- 45 Fahey, T.J., 1998: Recent Changes in an Upland Forest in South-Central New York. *Journal of the Torrey Botanical*  
46 *Society*, **125(1)**, 51-59.
- 47 Fall, S., Niyogi, D., Gluhovsky, A., Pielke, R.A., Kalnay, E., and Rochon, G., 2010: Impacts of land use land cover  
48 on temperature trends over the continental United States: assessment using the North American Regional  
49 Reanalysis. *International Journal of Climatology*, **30(13)**, 1980-1993.
- 50 Falloon, P.D., Dankers, R., Betts, R.A., Jones, C.D., Booth, B.B.B., and Lambert, F.H., 2012: Role of vegetation  
51 change in future climate under the A1B scenario and a climate stabilisation scenario, using the HadCM3C earth  
52 systems model. *Biogeosciences*, **9(11)**, 4739-4756.
- 53 FAO, 2005: *Forestry Paper 147 Global Forest Resources Assessment*. Series 147, 350 pp.
- 54 FAO, 2010a: *Global Forest Resources Assessment 2010*. FAO Forestry Paper Series 163, Rome, Italy, 340 pp.

- 1 FAO, 2010b: *Global Forest Resources Assessment 2010*. Rome, Italy, 12 pp.
- 2 Fargione, J., 2011: ENERGY Boosting biofuel yields. *Nature Climate Change*, **1(9)**, 445-446.
- 3 Farquhar, G.D., von Caemmerer, S., and Berry, J.A., 1980: A biochemical model of photosynthetic CO<sub>2</sub>
- 4 assimilation in leaves of C3 species. *Planta*, **149**, 78-90.
- 5 Fay, P.A., Carlisle, J.D., Knapp, A.K., Blair, J.M., and Collins, S.L., 2003: Productivity Responses to Altered
- 6 Rainfall Patterns in a C-4-Dominated Grassland. *Oecologia*, **137(2)**, 245-251.
- 7 Fay, P.A., Kaufman, D.M., Nippert, J.B., Carlisle, J.D., and Harper, C.W., 2008: Changes in grassland ecosystem
- 8 function due to extreme rainfall events: implications for responses to climate change. *Global Change Biology*,
- 9 **14(7)**, 1600-1608.
- 10 Fearnside, P.M., 2005: Do hydroelectric dams mitigate global warming? The case of Brazil's Curua-Una Dam.
- 11 *Mitigation and Adaptation Strategies for Global Change*, **10**, 675-691.
- 12 Feeley, K.J., and Rehm, E.M., 2012: Amazon's vulnerability to climate change heightened by deforestation and
- 13 man-made dispersal barriers. *Global Change Biology*, **18(12)**, 3606-3614.
- 14 Fellows, A.W., and Goulden, M.L., 2012: Rapid vegetation redistribution in Southern California during the early
- 15 2000s drought. *Journal of Geophysical Research: Biogeosciences*, **117(G3)**, G03025.
- 16 Fensham, R.J., Fairfax, R.J., and Dwyer, J.M., 2012: Potential aboveground biomass in drought-prone forest used
- 17 for rangeland pastoralism. *Ecological Applications*, **22(3)**, 894-908.
- 18 Fensham, R.J., Fairfax, R.J., and Ward, D.P., 2009: Drought-induced tree death in savanna. *Global Change Biology*,
- 19 **15**, 380-387.
- 20 Fensholt, R., Langanke, T., Rasmussen, K., Reenberg, A., Prince, S.D., Tucker, C., Scholes, B., Le, Q.B., Bondeau,
- 21 A., Eastman, R., Epstein, H., Gaughan, A.E., Hellden, U., Mbow, C., Olsson, L., Paruelo, J., Schweitzer, C.,
- 22 Seaquist, J., and Wessels, K., 2012: Greenness in semi-arid areas across the globe 1981-2007 - an Earth
- 23 Observing Satellite based analysis of trends and drivers. *Remote Sensing of Environment*, **121**, 144-158.
- 24 Ferriere, R., and Legendre, S., 2013: Eco-evolutionary feedbacks, adaptive dynamics and evolutionary rescue
- 25 theory. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **368(1610)**.
- 26 Ficke, A.D., Myrick, C.A., and Hansen, L.J., 2007: Potential impacts of global climate change on freshwater
- 27 fisheries. *Reviews in Fish Biology and Fisheries*, **17(4)**, 581-613.
- 28 Field, C.B., Lobell, D.B., Peters, H.A., and Chiariello, N.R., 2007: Feedbacks of terrestrial ecosystems to climate
- 29 change. *Annual Review of Environment and Resources*, **32**, 1-29.
- 30 Findell, K.L., Shevliakova, E., Milly, P.C.D., and Stouffer, R.J., 2007: Modeled impact of anthropogenic land cover
- 31 change on climate. *Journal of Climate*, **20(14)**, 3621-3634.
- 32 Finzi, A.C., Norby, R.J., Calfapietra, C., Gallet-Budynek, A., Gielen, B., Holmes, W.E., Hoosbeek, M.R., Iversen,
- 33 C.M., Jackson, R.B., Kubiske, M.E., Ledford, J., Liberloo, M., Oren, R., Polle, A., Pritchard, S., Zak, D.R.,
- 34 Schlesinger, W.H., and Ceulemans, R., 2007: Increases in nitrogen uptake rather than nitrogen-use efficiency
- 35 support higher rates of temperate forest productivity under elevated CO<sub>2</sub>. *Proceedings of the National Academy*
- 36 *of Sciences*, **104(35)**, 14014-14019.
- 37 Fiorese, G., and Guariso, G., 2013: Modeling the role of forests in a regional carbon mitigation plan. *Renewable*
- 38 *Energy*, **52**, 175-182.
- 39 Fischer, J., and Lindenmayer, D.B., 2007: Landscape modification and habitat fragmentation: a synthesis. *Global*
- 40 *Ecology and Biogeography*, **16(3)**, 265-280.
- 41 Fischlin, A., Midgley, G.F., Price, J.T., Leemans, R., Gopal, B., urley, C., Rounsevell, M.D.A., Dube, O.P.,
- 42 Tarazona, J., and Velichko, A.A., 2007: Ecosystems, their properties, goods, and services. Climate Change
- 43 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment
- 44 Report of the Intergovernmental Panel on Climate Change. In *Fourth Assessment Report of the*
- 45 *Intergovernmental Panel on Climate Change* [M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden
- 46 & C. E. Hanson (eds.)]. Cambridge University Press, Cambridge, pp. 211-272.
- 47 Fisher, J.B., Hurtt, G., Thomas, R.Q., and Chambers, J.Q., 2008: Clustered disturbances lead to bias in large-scale
- 48 estimates based on forest sample plots. *Ecology Letters*, **11(6)**, 554-563.
- 49 Fisher, R., McDowell, N., Purves, D., Moorcroft, P., Sitch, S., Cox, P., Huntingford, C., Meir, P., and Ian
- 50 Woodward, F., 2010: Assessing uncertainties in a second-generation dynamic vegetation model caused by
- 51 ecological scale limitations. *New Phytologist*, **187(3)**, 666-681.
- 52 FLUXNET, 2012: Historical Site Status, from [http://fluxnet.ornl.gov/site\\_status](http://fluxnet.ornl.gov/site_status).

- 1 Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., and Holling, C.S., 2004: Regime  
2 shifts, resilience, and biodiversity in ecosystem management. *Annual Review of Ecology Evolution and*  
3 *Systematics*, **35**, 557-581.
- 4 Forbes, B.C., Fauria, M.M., and Zetterberg, P., 2010: Russian Arctic warming and ‘greening’ are closely tracked by  
5 tundra shrub willows. *Global Change Biology*, **16(5)**, 1542-1554.
- 6 Fordham, D.A., Akcakaya, H.R., Araujo, M.B., Elith, J., Keith, D.A., Pearson, R., Auld, T.D., Mellin, C., Morgan,  
7 J.W., Regan, T.J., Tozer, M., Watts, M.J., White, M., Wintle, B.A., Yates, C., and Brook, B.W., 2012: Plant  
8 extinction risk under climate change: are forecast range shifts alone a good indicator of species vulnerability to  
9 global warming? *Global Change Biology*, **18(4)**, 1357-1371.
- 10 Franklin, J., Davis, F.W., Ikegami, M., Syphard, A.D., Flint, L.E., Flint, A.L., and Hannah, L., 2013: Modeling plant  
11 species distributions under future climates: how fine scale do climate projections need to be? *Global Change*  
12 *Biology*, **19(2)**, 473-483.
- 13 Franks, S.J., and Hoffmann, A.A., 2012: Genetics of Climate Change Adaptation. *Annual Review of Genetics*, Vol  
14 **46**, 185-208.
- 15 Franks, S.J., and Weis, A.E., 2008: A change in climate causes rapid evolution of multiple life-history traits and  
16 their interactions in an annual plant. *Journal of Evolutionary Biology*, **21(5)**, 1321-1334.
- 17 Frelich, L.E., Peterson, R.O., Dovciak, M., Reich, P.B., Vucetich, J.A., and Eisenhauer, N., 2012: Trophic cascades,  
18 invasive species and body-size hierarchies interactively modulate climate change responses of ecotonal  
19 temperate-boreal forest. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **367(1605)**,  
20 2955-2961.
- 21 Frolking, S., Talbot, J., Jones, M.C., Treat, C.C., Kauffman, J.B., Tuittila, E.S., and Roulet, N., 2011: Peatlands in  
22 the Earth's 21st century climate system. *Environmental Reviews*, **19**, 371-396.
- 23 Gagen, M., Finsinger, W., Wagner-Cremer, F., McCarroll, D., Loader, N.J., Robertson, I., Jalkanen, R., Young, G.,  
24 and Kirchhefer, A., 2011: Evidence of changing intrinsic water-use efficiency under rising atmospheric CO<sub>2</sub>  
25 concentrations in Boreal Fennoscandia from subfossil leaves and tree ring  $\delta^{13}C$  ratios. *Global Change Biology*,  
26 **17(2)**, 1064-1072.
- 27 Galiano, L., Martínez-Vilalta, J., and Lloret, F., 2010: Drought-Induced Multifactor Decline of Scots Pine in the  
28 Pyrenees and Potential Vegetation Change by the Expansion of Co-occurring Oak Species. *Ecosystems*, **13(7)**,  
29 978-991.
- 30 Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z.C., Freney, J.R., Martinelli, L.A., Seitzinger,  
31 S.P., and Sutton, M.A., 2008: Transformation of the nitrogen cycle: Recent trends, questions, and potential  
32 solutions. *Science*, **320(5878)**, 889-892.
- 33 Ganey, J.L., and Vojta, S.C., 2011: Tree mortality in drought-stressed mixed-conifer and ponderosa pine forests,  
34 Arizona, USA. *Forest Ecology and Management*, **261(1)**, 162-168.
- 35 Gao, J., and Liu, Y., 2011: Climate warming and land use change in Heilongjiang Province, Northeast China.  
36 *Applied Geography*, **31(2)**, 476-482.
- 37 Gao, X.J., and Giorgi, F., 2008: Increased aridity in the Mediterranean region under greenhouse gas forcing  
38 estimated from high resolution simulations with a regional climate model. *Global and Planetary Change*, **62(3-4)**,  
39 195-209.
- 40 Garcia-Carreras, L., and Parker, D.J., 2011: How does local tropical deforestation affect rainfall? *Geophysical*  
41 *Research Letters*, **38(19)**, L19802.
- 42 Garcia-Carreras, L., Parker, D.J., Taylor, C.M., Reeves, C.E., and Murphy, J.G., 2010: Impact of mesoscale  
43 vegetation heterogeneities on the dynamical and thermodynamic properties of the planetary boundary layer.  
44 *Journal of Geophysical Research*, **115**, D03102.
- 45 Garreta, V., Miller, P.A., Guiot, J., Hely, C., Brewer, S., Sykes, M.T., and Litt, T., 2010: A method for climate and  
46 vegetation reconstruction through the inversion of a dynamic vegetation model. *Climate Dynamics*, **35(2-3)**,  
47 371-389.
- 48 Garrity, S.R., C.D., A., McDowell, N., and Cai, M., in review: Two decades of climate-related tree mortality in the  
49 forests and woodlands of northern New Mexico, USA. *Ecological Applications*.
- 50 Gaudnik, C., Corcket, E., Clement, B., Delmas, C.E.L., Gombert-Courvoisier, S., Muller, S., Stevens, C.J., and  
51 Alard, D., 2011: Detecting the footprint of changing atmospheric nitrogen deposition loads on acid grasslands in  
52 the context of climate change. *Global Change Biology*, **17(11)**, 3351-3365.
- 53 Gedalof, Z., and Berg, A.A., 2010: Tree ring evidence for limited direct CO<sub>2</sub> fertilization of forests over the 20th  
54 century. *Global Biogeochemical Cycles*, **24(GB3027)**, 1-6.

- 1 Giardina, C.P., and Ryan, M.G., 2000: Evidence that decomposition rates of organic carbon in mineral soil do not  
2 vary with temperature. *Nature*, **404(6780)**, 858-861.
- 3 Gibson, D.J., and Hulbert, L.C., 1987: Effects of Fire, Topography and Year-to-Year Climatic Variation on Species  
4 Composition in Tallgrass Prairie. *Vegetatio*, **72(3)**, 175 -185.
- 5 Gibson, L., Lee, T.M., Koh, L.P., Brook, B.W., Gardner, T.A., Barlow, J., Peres, C.A., Bradshaw, C.J.A., Laurance,  
6 W.F., Lovejoy, T.E., and Sodhi, N.S., 2011: Primary forests are irreplaceable for sustaining tropical  
7 biodiversity. *Nature*, **478(7369)**, 378.
- 8 Gienapp, P., Lof, M., Reed, T.E., McNamara, J., Verhulst, S., and Visser, M.E., 2013: Predicting demographically  
9 sustainable rates of adaptation: can great tit breeding time keep pace with climate change? *Philosophical*  
10 *Transactions of the Royal Society B-Biological Sciences*, **368(1610)**.
- 11 Gienapp, P., Teplitsky, C., Alho, J.S., Mills, J.A., and Merila, J., 2008: Climate change and evolution: disentangling  
12 environmental and genetic responses. *Molecular Ecology*, **17(1)**, 167-178.
- 13 Gill, A.M., Wionarski, J.Z., and York, A., 1999: *Australians biodiversity responses to fire: Plants, birds and*  
14 *invertebrates*. Commonwealth Department of the Environment and Heritage, Canberra, Australia, 267 pp.
- 15 Gill, J.L., Williams, J.W., Jackson, S.T., Lininger, K.B., and Robinson, G.S., 2009: Pleistocene Megafaunal  
16 Collapse, Novel Plant Communities, and Enhanced Fire Regimes in North America. *Science*, **326(5956)**, 1100-  
17 1103.
- 18 Gillingham, P.K., Huntley, B., Kunin, W.E., and Thomas, C.D., 2012: The effect of spatial resolution on projected  
19 responses to climate warming. *Diversity and Distributions*, **18(10)**, 990-1000.
- 20 Girardin, M.P., and Mudelsee, M., 2008: Past and future changes in Canadian boreal wildfire activity. *Ecological*  
21 *Applications*, **18(2)**, 391-406.
- 22 Goetz, S.J., Epstein, H.E., Bhatt, U., Jia, G.J., Kaplan, J.O., Lischke, H., Yu, Q., Bunn, A., Lloyd, A., Alcaraz, D.,  
23 Beck, P.S.A., Comiso, J., Reynolds, M.K., and Walker, D.A., 2011: Recent changes in Arctic vegetation:  
24 satellite observations and simulation model predictions. In *Eurasian Arctic Land Cover and Land Use in a*  
25 *Changing Climate* [G. Gutman & A. Reissell (eds.)]. Springer-Verlag, Amsterdam, pp. 9-36.
- 26 Goetz, S.J., Mack, M.C., Gurney, K.R., Randerson, J.T., and Houghton, R.A., 2007: Ecosystem responses to recent  
27 climate change and fire disturbance at northern high latitudes: observations and model results contrasting  
28 northern Eurasia and North America. *Environmental Research Letters*, **2(4)**.
- 29 Goldblum, D., and Rigg, L.S., 2010: The deciduous forest – boreal forest ecotone. *Geography Compass*, **4(7)**, 701-  
30 717.
- 31 Golding, N., and Betts, R., 2008: Fire risk in Amazonia due to climate change in the HadCM3 climate model:  
32 Potential interactions with deforestation. *Global Biogeochemical Cycles*, **22(4)**, 1-10.
- 33 Gonzalez, P., 2001: Desertification and a shift of forest species in the West African Sahel. *Climate Research*, **17(2)**,  
34 217-228.
- 35 Gonzalez, P., Neilson, R.P., Lenihan, J.M., and Drapek, R.J., 2010: Global patterns in the vulnerability of  
36 ecosystems to vegetation shifts due to climate change. *Global Ecology and Biogeography*, **19(6)**, 755-768.
- 37 Gonzalez, P., Tucker, C.J., and Sy, H., 2012: Tree density and species decline in the African Sahel attributable to  
38 climate. *Journal of Arid Environments*, **78(0)**, 55-64.
- 39 Good, P., Caesar, J., Bernie, D., Lowe, J.A., van der Linden, P., Gosling, S.N., Warren, R., Arnell, N.W., Smith, S.,  
40 Bamber, J., Payne, T., Laxon, S., Srokosz, M., Sitch, S., Gedney, N., Harris, G., Hewitt, H., Jackson, L., Jones,  
41 C.D., O'Connor, F., Ridley, J., Vellinga, M., Halloran, P., and McNeall, D., 2011: A review of recent  
42 developments in climate change science. Part I: Understanding of future change in the large-scale climate  
43 system. *Progress in Physical Geography*, **35(3)**, 281-296.
- 44 Good, P., Jones, C., Lowe, J., Betts, R., and Gedney, N., 2013: Comparing Tropical Forest Projections from Two  
45 Generations of Hadley Centre Earth System Models, HadGEM2-ES and HadCM3LC. *Journal of Climate*,  
46 **26(2)**, 495-511.
- 47 Gordo, O., 2007: Why are bird migration dates shifting? A review of weather and climate effects on avian migratory  
48 phenology. *Climate Research*, **35(1-2)**, 37-58.
- 49 Gordo, O., and Sanz, J.J., 2005: Phenology and climate change: a long-term study in a Mediterranean locality.  
50 *Oecologia*, **146(3)**, 484-495.
- 51 Gordo, O., and Sanz, J.J., 2009: Long-term temporal changes of plant phenology in the Western Mediterranean.  
52 *Global Change Biology*, **15(8)**, 1930-1948.
- 53 Gottfried, M., Pauli, H., Futschik, A., Akhalkatsi, M., Barancok, P., Alonso, J.L.B., Coldea, G., Dick, J.,  
54 Erschbamer, B., Calzado, M.R.F., Kazakis, G., Krajci, J., Larsson, P., Mallaun, M., Michelsen, O., Moiseev, D.,

- 1 Moiseev, P., Molau, U., Merzouki, A., Nagy, L., Nakhutsrishvili, G., Pedersen, B., Pelino, G., Puscas, M.,  
2 Rossi, G., Stanisci, A., Theurillat, J.P., Tomaselli, M., Villar, L., Vittoz, P., Vogiatzakis, I., and Grabherr, G.,  
3 2012: Continent-wide response of mountain vegetation to climate change. *Nature Climate Change*, **2(2)**, 111-  
4 115.
- 5 Graiprab, P., Pongput, K., Tangtham, N., and Gassman, P.W., 2010: Hydrologic evaluation and effect of climate  
6 change on the At Samat watershed, Northeastern Region, Thailand. *International Agricultural Engineering*  
7 *Journal*, **19(2)**, 12-22.
- 8 Green, R.E., Collingham, Y.C., Willis, S.G., Gregory, R.D., Smith, K.W., and Huntley, B., 2008: Performance of  
9 climate envelope models in retrodicting recent changes in bird population size from observed climatic change.  
10 *Biology Letters*, **4(5)**, 599-602.
- 11 Griesbauer, H.P., and Green, D.S., 2012: Geographic and temporal patterns in white spruce climate-growth  
12 relationships in Yukon, Canada. *Forest Ecology and Management*, **267**, 215-227.
- 13 Grime, J.P., Fridley, J.D., Askew, A.P., Thompson, K., Hodgson, J.G., and Bennet, C.R., 2008: Long-term  
14 resistance to simulated climate change in an infertile grassland. *Proceeding of the National Academy of Science*,  
15 **105(29)**, 10028-10032.
- 16 Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., and Briggs, J.M., 2008: Global  
17 Change and the Ecology of Cities. *Science*, **319(5864)**, 756-760.
- 18 Grosse, G., Harden, J., Turetsky, M., McGuire, A.D., Camill, P., Tarnocai, C., Froking, S., Schuur, E.A.G.,  
19 Jorgenson, T., Marchenko, S., Romanovsky, V., Wickland, K.P., French, N., Waldrop, M., Bourgeau-Chavez,  
20 L., and Striegl, R.G., 2011: Vulnerability of high-latitude soil organic carbon in North America to disturbance.  
21 *Journal of Geophysical Research-Biogeosciences*, **116**.
- 22 Gruber, N., and Galloway, J.N., 2008: An Earth-system perspective of the global nitrogen cycle. *Nature*, **451(7176)**,  
23 293-296.
- 24 Gunderson, A.R., and Leal, M., 2012: Geographic variation in vulnerability to climate warming in a tropical  
25 Caribbean lizard. *Functional Ecology*, **26(4)**, 783-793.
- 26 Gunderson, C.A., Edwards, N.T., Walker, A.V., O'Hara, K.H., Campion, C.M., and Hanson, P.J., 2012: Forest  
27 phenology and a warmer climate - growing season extension in relation to climatic provenance. *Global Change*  
28 *Biology*, **18(6)**, 2008-2025.
- 29 Gunderson, L., and Holling, C.S. (eds.), 2001: *Panarchy: Understanding Transformations in Systems of Humans*  
30 *and Nature*. Island Press, pp. 507.
- 31 Gyllström, M., Hansson, L.A., Jeppesen, E., Garcia-Criado, F., Gross, E., Irvine, K., Kairesalo, T., Kornijow, R.,  
32 Miracle, M.R., Nykanen, M., Noges, T., Romo, S., Stephen, D., Van Donk, E., and Moss, B., 2005: The role of  
33 climate in shaping zooplankton communities of shallow lakes. *Limnology and Oceanography*, **50(6)**, 2008-  
34 2021.
- 35 Hague, M.J., Ferrari, M.R., Miller, J.R., Patterson, D.A., Russell, G.L., Farrell, A.P., and Hinch, S.G., 2011:  
36 Modelling the future hydroclimatology of the lower Fraser River and its impacts on the spawning migration  
37 survival of sockeye salmon. *Global Change Biology*, **17(1)**, 87-98.
- 38 Haider, S., Kueffer, C., Edwards, P.J., and Alexander, J.M., 2012: Genetically based differentiation in growth of  
39 multiple non-native plant species along a steep environmental gradient. *Oecologia*, **170(1)**, 89-99.
- 40 Hall, J.S., Ashton, M.S., Garen, E.J., and Jose, S., 2011: The ecology and ecosystem services of native trees:  
41 Implications for reforestation and land restoration in Mesoamerica. *Forest Ecology and Management*, **261(10)**,  
42 1553-1557.
- 43 Halley, J.M., Iwasa, Y., and Vokou, D., 2013: Comment on "Extinction Debt and Windows of Conservation  
44 Opportunity in the Brazilian Amazon". *Science*, **339(6117)**, 271.
- 45 Hamilton, S.K., 2010: Biogeochemical implications of climate change for tropical rivers and floodplains.  
46 *Hydrobiologia*, **657(1)**, 19-35.
- 47 Hampe, A., 2011: Plants on the move: The role of seed dispersal and initial population establishment for climate-  
48 driven range expansions. *Acta Oecologica-International Journal of Ecology*, **37(6)**, 666-673.
- 49 Han, S.J., Xu, D., and Wang, S.L., 2012: Decreasing potential evaporation trends in China from 1956 to 2005:  
50 Accelerated in regions with significant agricultural influence? *Agricultural and Forest Meteorology*, **154-155**,  
51 44-56.
- 52 Hannah, L., 2012: *Saving a Million Species: Extinction Risk from Climate Change*. Island Press, Washington  
53 London, 419 pp.

- 1 Hannah, L., Midgley, G., Anelman, S., Araujo, M., Hughes, G., Martinez-Meyer, E., Pearson, R., and Williams, P.,  
2 2007: Protected area needs in a changing climate. *Frontiers in Ecology and the Environment*, **5(3)**, 131-138.
- 3 Hansen, M.M., Olivieri, I., Waller, D.M., Nielsen, E.E., and Grp, G.W., 2012: Monitoring adaptive genetic  
4 responses to environmental change. *Molecular Ecology*, **21(6)**, 1311-1329.
- 5 Hanson, P.J., Wullschleger, S.D., Norby, R.J., Tschaplinski, T.J., and Gunderson, C.A., 2005: Importance of  
6 changing CO<sub>2</sub>, temperature, precipitation, and ozone on carbon and water cycles of an upland oak forest:  
7 incorporating experimental results into model simulations. *Global Change Biology*, **11**, 1402-1423.
- 8 Hari, P., and Kulmata, L., 2008: *Boreal Forest and Climate Change*. Springer, New York, 582 pp.
- 9 Harris, J.A., Hobbs, R.J., Higgs, E., and Aronson, J., 2006: Ecological Restoration and Global Climate Change.  
10 *Restoration Ecology*, **14**, 170-176.
- 11 Harrison, S.P., and Goni, M.F.S., 2010: Global patterns of vegetation response to millennial-scale variability and  
12 rapid climate change during the last glacial period. *Quaternary Science Reviews*, **29(21-22)**, 2957-2980.
- 13 Hartmann, D., Klein Tank, A., and others, in press: Observations: Atmosphere and Surface. In *The Physical Science*  
14 *Basis: Contribution of Working Group I to the 5th Assessment Report of the Intergovernmental Panel on*  
15 *Climate Change* [T. F. Stocker (ed.)]. pp.
- 16 Hastings, A., 2004: Transients: the key to long-term ecological understanding? *Trends in Ecology & Evolution*,  
17 **19(1)**, 39-45.
- 18 Haxeltine, A., and Prentice, I.C., 1996: BIOME3: an equilibrium terrestrial biosphere model based on  
19 ecophysiological constraints, resource availability, and competition among plant functional types. *Global*  
20 *Biogeochemical Cycles*, **10**, 693-709.
- 21 Hayes, F., Jones, M.L.M., Mills, G., and Ashmore, M., 2007: Meta-analysis of the relative sensitivity of semi-  
22 natural vegetation species to ozone. *Environmental Pollution*, **146(3)**, 754-762.
- 23 Haywood, A.M., Ridgwell, A., Lunt, D.J., Hill, D.J., Pound, M.J., Dowsett, H.J., Dolan, A.M., Francis, J.E., and  
24 Williams, M., 2011: Are there pre-Quaternary geological analogues for a future greenhouse warming?  
25 *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*,  
26 **369(1938)**, 933-956.
- 27 Haywood, A.M., and Valdes, P.J., 2006: Vegetation cover in a warmer world simulated using a dynamic global  
28 vegetation model for the Mid-Pliocene. *Palaeogeography Palaeoclimatology Palaeoecology*, **237(2-4)**, 412-  
29 427.
- 30 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  
31 monsoon in China. *Advances in Atmospheric Sciences*, **24(6)**, 972-992.
- 32 Heckenberger, M.J., Russell, J.C., Toney, J.R., and Schmidt, M.J., 2007: The legacy of cultural landscapes in the  
33 Brazilian Amazon: implications for biodiversity. *Philosophical Transactions of the Royal Society B-Biological*  
34 *Sciences*, **362(1478)**, 197-208.
- 35 Hegarty, M.J., 2012: Invasion of the hybrids. *Molecular Ecology*, **21(19)**, 4669-4671.
- 36 Hegglin, M.I., and Shepherd, T.G., 2009: Large climate-induced changes in ultraviolet index and stratosphere-to-  
37 troposphere ozone flux. *Nature Geoscience*, **10(10)**, 687- 691.
- 38 Heggland, S.J., Nielsen, A., Lazaro, A., Bjerknes, A.L., and Totland, 2009: How does climate warming affect plant-  
39 pollinator interactions? *Ecology Letters*, **12(2)**, 184-195.
- 40 Hellden, U., and Tottrup, C., 2008: Regional desertification: A global synthesis. *Global and Planetary Change*,  
41 **64(3-4)**, 169-176.
- 42 Heller, N.E., and Zavaleta, E.S., 2009: Biodiversity management in the face of climate change: A review of 22 years  
43 of recommendations. *Biological Conservation*, **142(1)**, 14-32.
- 44 Hellmann, J.J., Byers, J.E., Bierwagen, B.G., and Dukes, J.S., 2008: Five potential consequences of climate change  
45 for invasive species. *Conservation Biology*, **22(3)**, 534-543.
- 46 Hemery, G.E., 2008: Forest management and silvicultural responses to projected climate change impacts on  
47 European broadleaved trees and forests. *International Forestry Review*, **10(4)**, 591-607.
- 48 Hermoso, V., and Clavero, M., 2011: Threatening processes and conservation management of endemic freshwater  
49 fish in the Mediterranean basin: a review. *Marine and Freshwater Research*, **62(3)**, 244-254.
- 50 Heubes, J., Kühn, I., König, K., Wittig, R., Zizka, G., and Hahn, K., 2011: Modelling biome shifts and tree cover  
51 change for 2050 in West Africa. *Journal of Biogeography*, **38(12)**, 2248-2258.
- 52 Hewitt, N., Klenk, N., Smith, A.L., Bazely, D.R., Yan, N., Wood, S., MacLellan, J.I., Lipsig-Mumme, C., and  
53 Henriques, I., 2011: Taking stock of the assisted migration debate. *Biological Conservation*, **144(11)**, 2560-  
54 2572.

- 1 Hickler, T., Eklundh, L., Seaquist, J.W., Smith, B., Ardo, J., Olsson, L., Sykes, M.T., and Sjöström, M., 2005:  
2 Precipitation controls Sahel greening trend. *Geophysical Research Letters*, **32(L21415)**, 1-4.
- 3 Hickler, T., Smith, B., Prentice, I.C., Mjöfors, K., Miller, P., Arneth, A., and Sykes, M.T., 2008: CO<sub>2</sub> fertilization in  
4 temperate FACE experiments not representative of boreal and tropical forests. *Global Change Biology*, **14**,  
5 1531-1542.
- 6 Hickler, T., Vohland, K., Feehan, J., Miller, P.A., Smith, B., Costa, L., Giesecke, T., Fronzek, S., Carter, T.R.,  
7 Cramer, W., Kühn, I., and Sykes, M.T., 2012: Projecting the future distribution of European potential natural  
8 vegetation zones with a generalized, tree species-based dynamic vegetation model. *Global Ecology and*  
9 *Biogeography*, **21(1)**, 50-63.
- 10 Higgins, S.I., Clark, J.S., Nathan, R., Hovestadt, T., Schurr, F., Fragoso, J.M.V., Aguiar, M.R., Ribbens, E., and  
11 Lavorel, S., 2003: Forecasting plant migration rates: managing uncertainty for risk assessment. *Journal of*  
12 *Ecology*, **91(3)**, 341-347.
- 13 Higgins, S.I., and Scheiter, S., 2012: Atmospheric CO<sub>2</sub> forces abrupt vegetation shifts locally, but not globally.  
14 *Nature*, **488(7410)**, 209-212.
- 15 Higuera, P.E., Chipman, M.L., Barnes, J.L., Urban, M.A., and Hu, F.S., 2011: Variability of tundra fire regimes in  
16 Arctic Alaska: millennial-scale patterns and ecological implications. *Ecological Applications*, **21(8)**, 3211-3226.
- 17 Hill, P.W., Farrar, J., Roberts, P., Farrell, M., Grant, H., Newsham, K.K., Hopkins, D.W., Bardgett, R.D., and Jones,  
18 D.L., 2011: Vascular plant success in a warming Antarctic may be due to efficient nitrogen acquisition. *Nature*  
19 *Clim. Change*, **1(1)**, 50-53.
- 20 Hinzman, L.D., Bettez, N.D., Bolton, W.R., Chapin III, F.S., Dyrurgerov, M.B., Fastie, C.L., Griffith, B., Hollister,  
21 R.D., Hope, A., Huntington, H.P., Jensen, A.M., Jia, G.J., Jorgenson, T., Kane, D.L., Klein, D.R., Kofinas, G.,  
22 Lynch, A.H., Lloyd, A.H., McGuire, A.D., Nelson, F.E., Oechel, W.C., Osterkamp, T.E., Racine, C.H.,  
23 Romanovsky, V.E., Stone, R.S., Stow, D.A., Sturm, M., Tweedie, C.E., Vourlitis, G.L., Walker, M.D., Walker,  
24 D.A., Webber, P.J., Welker, J.M., Winker, K., and Yoshikawa, K., 2005: Evidence and implications of recent  
25 climate change in northern Alaska and other arctic regions. *Climatic Change*, **72(3)**, 251-298.
- 26 Hockey, P.A.R., Sirami, C., Ridley, A.R., Midgley, G.F., and Babiker, H.A., 2011: Interrogating recent range  
27 changes in South African birds: confounding signals from land use and climate change present a challenge for  
28 attribution. *Diversity and Distributions*, **17(2)**, 254-261.
- 29 Hodgson, J.A., Thomas, C.D., Dytham, C., Travis, J.M.J., and Cornell, S.J., 2012: The Speed of Range Shifts in  
30 Fragmented Landscapes. *PLoS One*, **7(10)**.
- 31 Hoegh-Guldberg, O., Hughes, L., McIntyre, S., Lindenmayer, D.B., Parmesan, C., Possingham, H.P., and Thomas,  
32 C.D., 2008: Assisted colonization and rapid climate change. *Science*, **321(5887)**, 345-346.
- 33 Hof, C., Levinsky, I., Araujo, M.B., and Rahbek, C., 2011: Rethinking species' ability to cope with rapid climate  
34 change. *Global Change Biology*, **17(9)**, 2987-2990.
- 35 Hoffmann, A.A., and Sgro, C.M., 2011: Climate change and evolutionary adaptation. *Nature*, **470(7335)**, 479-485.
- 36 Hofmann, G.E., and Todgham, A.E., 2010: Living in the Now: Physiological Mechanisms to Tolerate a Rapidly  
37 Changing Environment. *Annual Review of Physiology*, **72**, 127-145.
- 38 Hofmockel, K.S., Zak, D.R., Moran, K.K., and Jastrow, J.D., 2011: Changes in forest soil organic matter pools after  
39 a decade of elevated CO<sub>2</sub> and O<sub>3</sub>. *Soil Biology and Biochemistry*, **43(7)**, 1518-1527.
- 40 Hogg, E.H., Brandt, J.P., and Michaelian, M., 2008: Impact of a regional drought on the productivity, dieback and  
41 biomass of western Canadian aspen forests. *Canadian Journal of Forest Research*, **38**, 1373-1384,  
42 doi:1310.1139/X1308-1001.
- 43 Hole, D.G., Huntley, B., Arinaitwe, J., Butchart, S.H.M., Collingham, Y.C., Fishpool, L.D.C., Pain, D.J., and Willis,  
44 S.G., 2011: Toward a Management Framework for Networks of Protected Areas in the Face of Climate Change.  
45 *Conservation Biology*, **25(2)**, 305-315.
- 46 Hole, D.G., Willis, S.G., Pain, D.J., Fishpool, L.D., Butchart, S.H.M., Collingham, Y.C., Rahbek, C., and Huntley,  
47 B., 2009: Projected impacts of climate change on a continent-wide protected area network. *Ecology Letters*,  
48 **12(5)**, 420-431.
- 49 Holling, C.S., 1973: Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics*, **4**,  
50 1-23.
- 51 Holmgren, M., Stapp, P., Dickman, C.R., Gracia, C., Graham, S., Gutiérrez, J.R., Hice, C., Jaksic, F., Kelt, D.A.,  
52 Letnic, M., Lima, M., López, B.C., Meserve, P.L., Milstead, W.B., Polis, G.A., Previtalli, M.A., Richter, M.,  
53 Sabaté, S., and Squeo, F.A., 2006: Extreme climatic events shape arid and semiarid ecosystems. *Frontiers in*  
54 *Ecology and the Environment*, **4(2)**, 87-95.



- 1 Hooijer, A., Page, S., Canadell, J.G., Silvius, M., Kwadijk, J., Wosten, H., and Jauhiainen, J., 2010: Current and  
2 future CO<sub>2</sub> emissions from drained peatlands in Southeast Asia. *Biogeosciences*, **7(5)**, 1505-1514.
- 3 Hoover, S.E.R., Ladley, J.J., Shchepetkina, A.A., Tisch, M., Giese, S.P., and Tylianakis, J.M., 2012: Warming,  
4 CO<sub>2</sub>, and nitrogen deposition interactively affect a plant-pollinator mutualism. *Ecology Letters*, **15(3)**, 227-234.
- 5 Horowitz, L.W., 2006: Past present and future concentrations of tropospheric ozone and aerosols: methodology,  
6 ozone evaluation, and sensitivity to aerosol wet removal. *Journal of Geophysical Research - Atmospheres*,  
7 **111(D22211)**, 1-16.
- 8 Høye, T.T., Post, E., Mølte, H., Schmidt, N.M., and Forchhammer, M.C., 2007: Rapid advancement of spring in  
9 the High Arctic. *Current biology : CB*, **17(12)**, R449-R451.
- 10 Huang, D., Haack, R.A., and Zhang, R., 2011: Does global warming increase establishment rates of invasive alien  
11 species? A Centennial time series analysis. *PLoS One*, **6(9)**, 1-5.
- 12 Huang, J.G., Bergeron, Y., Denneler, B., Berninger, F., and Tardif, J., 2007: Response of forest trees to increased  
13 atmospheric CO<sub>2</sub>. *Critical Reviews in Plant Sciences*, **26(5-6)**, 265-283.
- 14 Hudson, I.L., and Keatley, M.R. (eds.), 2010: *Phenological Research*. Springer Dordrecht, Heidelberg, London,  
15 New York, pp. 522.
- 16 Huey, R.B., Kearney, M.R., Krockenberger, A., Holtum, J.A.M., Jess, M., and Williams, S.E., 2012: Predicting  
17 organismal vulnerability to climate warming: roles of behaviour, physiology and adaptation. *Philosophical  
18 Transactions of the Royal Society B-Biological Sciences*, **367(1596)**, 1665-1679.
- 19 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.,  
20 2006: Changes in aboveground primary production and carbon and nitrogen pools accompanying woody plant  
21 encroachment in a temperate savanna. *Global Change Biology*, **12(9)**, 1733-1747.
- 22 Hülber, K., Winkler, M., and Grabherr, G., 2010: Intraseasonal climate and habitat-specific variability controls the  
23 flowering phenology of high alpine plant species. *Functional Ecology*, **24(2)**, 245-252.
- 24 Hunter, C.M., Caswell, H., Runge, M.C., Regehr, E.V., Amstrup, S.C., and Stirling, I., 2010: Climate change  
25 threatens polar bear populations: a stochastic demographic analysis. *Ecology*, **91(10)**, 2883-2897.
- 26 Huntingford, C., Cox, P.M., Mercado, L.M., Sitch, S., Bellouin, N., Boucher, O., and Gedney, N., 2011: Highly  
27 contrasting effects of different climate forcing agents on terrestrial ecosystem services. *Philosophical  
28 Transactions of the Royal Society A-Mathematical, Physical and Engineering Sciences*, **369(1943)**, 2026-2037.
- 29 Huntingford, C., Zelazowski, P., Galbraith, D., Mercado, L.M., Sitch, S., Fisher, R., Lomas, M., P.Walker, A.,  
30 Jones, C.D., Booth, B.B.B., Malhi, Y., Hemming, D., Kay, G., Good, P., Lewis, S.L., Phillips, O.L., Atkin,  
31 O.K., Lloyd, J., Gloor, E., Zaragoza-Castells, J., Meir, P., Betts, R., Harris, P.P., Nobre, C., Marengo, J., and  
32 Cox, P.M., 2013: High resilience of tropical rainforests to climate change. *Nature Geoscience*.
- 33 Huntington, H.P., Goodstein, E., and Euskirchen, E., 2012: Towards a tipping point in responding to change: rising  
34 costs, fewer options for Arctic and global societies. *Ambio*, **41(1)**, 66-74.
- 35 Hurtt, G.C., Chini, L.P., Frothingham, S., Betts, R.A., Feddema, J., Fischer, G., Fisk, J.P., Hibbard, K., Houghton, R.A.,  
36 Janetos, A., Jones, C.D., Kindermann, G., Kinoshita, T., Goldewijk, K.K., Riahi, K., Shevliakova, E., Smith, S.,  
37 Stehfest, E., Thomson, A., Thornton, P., Vuuren, D.P.v., and Wang, Y.P., 2011: Harmonization of land-use  
38 scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and  
39 resulting secondary lands. *Climatic Change*, **109**, 117-161.
- 40 Husby, A., Visser, M.E., and Kruuk, L.E.B., 2011: Speeding Up Microevolution: The Effects of Increasing  
41 Temperature on Selection and Genetic Variance in a Wild Bird Population. *Plos Biology*, **9(2)**.
- 42 Hyvönen, R., Ågren, G.I., Linder, S., Persson, T., Cotrufo, M.F., Ekblad, A., Freeman, M., Grelle, A., Janssens,  
43 I.A., Jarvis, P.G., Kellomäki, S., Lindroth, A., Loustau, D., Lundmark, T., Norby, R.J., Oren, R., Pilegaard, K.,  
44 Ryan, M.G., Sigurdsson, B.D., Strömberg, M., Ojien, M.V., and Wallin, G., 2007: The likely impact of elevated  
45 [CO<sub>2</sub>], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and  
46 boreal forest ecosystems: a literature review. *New Phytologist*, **173(3)**, 463-480.
- 47 Ihlow, F., Dambach, J., Engler, J.O., Flecks, M., Hartmann, T., Nekum, S., Rajaei, H., and Rodder, D., 2012: On the  
48 brink of extinction? How climate change may affect global chelonian species richness and distribution. *Global  
49 Change Biology*, **18(5)**, 1520-1530.
- 50 Innes, J.L., 1992: Observations on the Condition of Beech (*Fagus sylvatica* L.) in Britain in 1990. *Forestry*, **65(1)**,  
51 35-60.
- 52 Inouye, D.W., 2008: Effects of climate change on phenology, frost damage, and floral abundance of montane  
53 wildflowers. *Ecology*, **89(2)**, 353-362.

- 1 INPE, 2012: Projeto Desmatamento (PRODES): Monitoramento da Floresta Amazonica por Satelite, 2009, from  
2 <http://www.obt.inpe.br/prodes/>.
- 3 IPCC, 2012: Summary for Policymakers. In *Managing the Risks of Extreme Events and Disasters to Advance*  
4 *Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on*  
5 *Climate Change* [C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K.  
6 J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor & P. M. Midgley (eds.)]. Cambridge University Press,  
7 Cambridge, UK, and New York, NY, USA, pp. 1-19.
- 8 Iverson, L., Prasad, A., and Matthews, S., 2008: Modeling potential climate change impacts on the trees of the  
9 northeastern United States. *Mitigation and Adaptation Strategies for Global Change*, **13(5-6)**, 487-516.
- 10 Iverson, L.R., Prasad, A.M., Matthews, S.N., and Peters, M.P., 2011: Lessons Learned While Integrating Habitat,  
11 Dispersal, Disturbance, and Life-History Traits into Species Habitat Models Under Climate Change.  
12 *Ecosystems*, **14(6)**, 1005-1020.
- 13 Iverson, L.R., Schwartz, M.W., and Prasad, A.M., 2004: How fast and far might tree species migrate in the eastern  
14 United States due to climate change? *Global Ecology and Biogeography*, **13(3)**, 209-219.
- 15 Jackson, S., and Weng, C. (1999). *Late quaternary extinction of a tree species in eastern North America*. Paper  
16 presented at the National Academy of Sciences USA.
- 17 Jackson, S.T., Gray, S.T., and Shuman, B., 2009: Paleocology and resource management in a dynamic landscape:  
18 case studies from the Rocky Mountain headwaters. In *Conservation Paleobiology: Using the Past to Manage*  
19 *for the Future* [G. P. Dietl & K. W. Flessa (eds.)]. The Paleontological Society, pp. 61-80.
- 20 Jackson, S.T., and Hobbs, R.J., 2009: Ecological Restoration in the Light of Ecological History. *Science*, **325(5940)**,  
21 567-569.
- 22 Jackson, S.T., and Overpeck, J.T., 2000: Responses of Plant Populations and Communities to Environmental  
23 Changes of the Late Quaternary. *Paleobiology*, **26(4)**, 194-220.
- 24 Jansen, E., J.T., O., and others, 2007: Chapter 6: Paleoclimate. In *Climate Change 2007: The Physical Science*  
25 *Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on*  
26 *Climate Change* [S. Solomon & e. al (eds.)]. Cambridge University Press. Cambridge, Cambridge, pp. 433-497.
- 27 Jaramillo, C., Ochoa, D., Contreras, L., Pagani, M., Carvajal-Ortiz, H., Pratt, L.M., Krishnan, S., Cardona, A.,  
28 Romero, M., Quiroz, L., Rodriguez, G., Rueda, M.J., de la Parra, F., Moron, S., Green, W., Bayona, G., Montes,  
29 C., Quintero, O., Ramirez, R., Mora, G., Schouten, S., Bermudez, H., Navarrete, R., Parra, F., Alvaran, M.,  
30 Osorno, J., Crowley, J.L., Valencia, V., and Vervoort, J., 2010: Effects of Rapid Global Warming at the  
31 Paleocene-Eocene Boundary on Neotropical Vegetation. *Science*, **330(6006)**, 957-961.
- 32 Jarvis, P.G., 1976: The interpretation of the variations in leaf water potential and stomatal conductance found in  
33 canopies in the field. *Philosophical Transactions of the Royal Society of London*, **B, 273**, 593-610.
- 34 Jenkins, K.M., and Boulton, A.J., 2007: Detecting impacts and setting restoration targets in arid-zone rivers: aquatic  
35 micro-invertebrate responses to reduced floodplain inundation. *Journal of Applied Ecology*, **44(4)**, 823-832.
- 36 Jensen, K.D., Beier, C., Michelsen, A., and Emmett, B.A., 2003: Effects of experimental drought on microbial  
37 processes in two temperate heathlands at contrasting water conditions. *Applied Soil Ecology*, **24(2)**, 165-176.
- 38 Jeong, S.J., Ho, C.H., Gim, H.J., and Brown, M.E., 2011: Phenology shifts at start vs. end of growing season in  
39 temperate vegetation over the Northern Hemisphere for the period 1982-2008. *Global Change Biology*, **17(7)**,  
40 2385-2399.
- 41 Jeppesen, E., Moss, B., Bennion, H., Carvalho, L., DeMeester, L., Feuchtmayr, H., Friberg, N., Gessner, M.O.,  
42 Hefting, M., Lauridsen, T.L., Liboriussen, L., Malmquist, H.J., May, L., Meerhoff, M., Olafsson, J.S., Soons,  
43 M.B., and Verhoeven, J.T.A., 2010: Interaction of Climate Change and Eutrophication. In *Climate Change*  
44 *Impacts on Freshwater Ecosystems*. Wiley-Blackwell, pp. 119-151.
- 45 Jia, B., Ma, Y., and Qiu, K., 2009a: Dynamics of the vegetation coverage in recent 15 years in Yijinhuluo County,  
46 Inner Mongolia, China. *Arid Land Geography*, **32(4)**, 481-487.
- 47 Jia, G.J., Epstein, H.E., and Walker, D.A., 2009b: Vegetation greening in the canadian arctic related to decadal  
48 warming. *Journal of Environmental Monitoring*, **11(12)**, 2231-2238.
- 49 Jin, J., Lu, S., Li, S., and Miller, N.L., 2010: Impact of Land Use Change on the Local Climate over the Tibetan  
50 Plateau. *Advances in Meteorology*, **2010(ID 837480)**, 1-6.
- 51 Jin, Y., Randerson, J.T., Goetz, S.J., Beck, P.S.A., Loranty, M.M., and Goulden, M.L., 2012: The influence of burn  
52 severity on postfire vegetation recovery and albedo change during early succession in North American boreal  
53 forests. *Journal of Geophys. Research Biogeosciences*, **117(G1)**, G01036, doi:01010.01029/02011jg001886.

- 1 Johanson, C.M., and Fu, Q., 2009: Hadley Cell Widening: Model Simulations versus Observations. *Journal of*  
2 *Climate*, **22(10)**, 2713-2725.
- 3 Johnk, K.D., Huisman, J., Sharples, J., Sommeijer, B., Visser, P.M., and Stroom, J.M., 2008: Summer heatwaves  
4 promote blooms of harmful cyanobacteria. *Global Change Biology*, **14(3)**, 495-512.
- 5 Johnson, W.C., Millett, B.V., Gilmanov, T., Voldseth, R.A., Guntenspergen, G.R., and Naugle, D.E., 2005:  
6 Vulnerability of northern prairie wetlands to climate change. *Bioscience*, **55(10)**, 863-872.
- 7 Johnstone, J.F., Hollingsworth, T.N., Chapin, F.S., and Mack, M.C., 2010: Changes in fire regime break the legacy  
8 lock on successional trajectories in Alaskan boreal forest. *Global Change Biology*, **16(4)**, 1281-1295.
- 9 Jones, C.D., Cox, P., and Huntingford, C., 2003: Uncertainty in climate-carbon-cycle projections associated with the  
10 sensitivity of soil respiration to temperature. *Tellus Series B-Chemical and Physical Meteorology*, **55(2)**, 642-  
11 648.
- 12 Jones, C.D., Hughes, J.K., Bellouin, N., Hardiman, S.C., Jones, G.S., Knight, J., Liddicoat, S., O'Connor, F.M.,  
13 Andres, R.J., Bell, C., Boo, K.O., Bozzo, A., Butchart, N., Cadule, P., Corbin, K.D., Doutriaux-Boucher, M.,  
14 Friedlingstein, P., Gornall, J., Gray, L., Halloran, P.R., Hurtt, G., Ingram, W.J., Lamarque, J.F., Law, R.M.,  
15 Meinshausen, M., Osprey, S., Palin, E.J., Chini, L.P., Raddatz, T., Sanderson, M.G., Sellar, A.A., Schurer, A.,  
16 Valdes, P., Wood, N., Woodward, S., Yoshioka, M., and Zerroukat, M., 2011: The HadGEM2-ES  
17 implementation of CMIP5 centennial simulations. *Geoscientific Model Development*, **4(3)**, 543-570.
- 18 Jongman, R.H.G., Bouwma, I.M., Griffioen, A., Jones-Walters, L., and Van Doorn, A.M., 2011: The Pan European  
19 Ecological Network: PEEN. *Landscape Ecology*, **26(3)**, 311-326.
- 20 Jorgenson, M.T., Romanovsky, V., Harden, J., Shur, Y., O'Donnell, J., Schuur, E.A.G., Kanevskiy, M., and  
21 Marchenko, S., 2010: Resilience and vulnerability of permafrost to climate change. *Canadian Journal of Forest*  
22 *Research*, **40(7)**, 1219-1236.
- 23 Joubert, D.F., Rothauge, A., and Smit, G.N., 2008: A conceptual model of vegetation dynamics in the semiarid  
24 Highland savanna of Namibia, with particular reference to bush thickening by *Acacia mellifera*. *Journal of Arid*  
25 *Environments*, **72(12)**, 2201-2210.
- 26 Jump, A.S., Hunt, J.M., Martinez-Izquierdo, J.A., and Penuelas, J., 2006: Natural selection and climate change:  
27 temperature-linked spatial and temporal trends in gene frequency in *Fagus sylvatica*. *Molecular Ecology*,  
28 **15(11)**, 3469-3480.
- 29 Jump, A.S., Peñuelas, J., Rico, L., Ramallo, E., Estiarte, M., Martínez-Izquierdo, J.A., and Lloret, F., 2008:  
30 Simulated climate change provokes rapid genetic change in the Mediterranean shrub *Fumana thymifolia*. *Global*  
31 *Change Biology*, **14(3)**, 637-643.
- 32 Jung, M., Reichstein, M., Ciais, P., Seneviratne, S.I., Sheffield, J., Goulden, M.L., Bonan, G., Cescatti, A., Chen,  
33 J.Q., de Jeu, R., Dolman, A.J., Eugster, W., Gerten, D., Gianelle, D., Gobron, N., Heinke, J., Kimball, J., Law,  
34 B.E., Montagnani, L., Mu, Q.Z., Mueller, B., Oleson, K., Papale, D., Richardson, A.D., Rouspard, O., Running,  
35 S., Tomelleri, E., Viovy, N., Weber, U., Williams, C., Wood, E., Zaehle, S., and Zhang, K., 2010: Recent  
36 decline in the global land evapotranspiration trend due to limited moisture supply. *Nature*, **467(7318)**, 951-954.
- 37 Kaiser, K.E., McGlynn, B.L., and Emanuel, R.E., 2012: Ecohydrology of an outbreak: mountain pine beetle impacts  
38 trees in drier landscape positions first. *Ecohydrology*, n/a-n/a.
- 39 Kane, J.M., Meinhardt, K.A., Chang, T., Cardall, B.L., Michalet, R., and Whitham, T.G., 2011: Drought-induced  
40 mortality of a foundation species (*Juniperus monosperma*) promotes positive afterlife effects in understory  
41 vegetation. *Plant Ecology*, **212(5)**, 733-741.
- 42 Kanniah, K.D., Beringer, J., North, P., and Hutley, L., 2012: Control of atmospheric particles on diffuse radiation  
43 and terrestrial plant productivity. *Progress in Physical Geography*, **36(2)**, 209-237.
- 44 Kappes, H., and Haase, P., 2012: Slow, but steady: dispersal of freshwater molluscs. *Aquatic Sciences*, **74(1)**, 1-14.
- 45 Karell, P., Ahola, K., Karstinen, T., Valkama, J., and Brommer, J.E., 2011: Climate change drives microevolution in  
46 a wild bird. *Nature Communications*, **2**, 1-7.
- 47 Karnosky, D.F., Pregitzer, K.S., Zak, D.R., Kubiske, M.E., Hendrey, G.R., Weinstein, D., Nosal, M., and Percy,  
48 K.E., 2005: Scaling ozone responses of forest trees to the ecosystem level in a changing climate. *Plant Cell and*  
49 *Environment*, **28(8)**, 965-981.
- 50 Kasischke, E.S., Verbyla, D.L., Rupp, T.S., McGuire, A.D., Murphy, K.A., Jandt, R., Barnes, J.L., Hoy, E.E., Duffy,  
51 P.A., Calef, M., and Turetsky, M.R., 2010: Alaska's changing fire regime — implications for the vulnerability  
52 of its boreal forests. *Canadian Journal of Forest Research*, **40(7)**, 1313-1324.
- 53 Kasson, M.T., and Livingston, W.H., 2012: Relationships among beech bark disease, climate, radial growth  
54 response and mortality of American beech in northern Maine, USA. *Forest Pathology*, **42(3)**, 199-212.

- 1 Kaufman, D.S., Schneider, D.P., McKay, N.P., Ammann, C.M., Bradley, R.S., Briffa, K.R., Miller, G.H., Otto-  
2 Bliesner, B.L., Overpeck, J.T., Vinther, B.M., and Arctic Lakes 2k Project, M., 2009: Recent Warming  
3 Reverses Long-Term Arctic Cooling. *Science*, **325(5945)**, 1236-1239.
- 4 Kaushal, S.S., Likens, G.E., Jaworski, N.A., Pace, M.L., Sides, A.M., Seekell, D., Belt, K.T., Secor, D.H., and  
5 Wingate, R.L., 2010: Rising stream and river temperatures in the United States. *Frontiers in Ecology and the*  
6 *Environment*, **8(9)**, 461-466.
- 7 Kearney, M., Porter, W.P., Williams, C., Ritchie, S., and Hoffmann, A.A., 2009: Integrating biophysical models and  
8 evolutionary theory to predict climatic impacts on species' ranges: the dengue mosquito *Aedes aegypti* in  
9 Australia. *Functional Ecology*, **23(3)**, 528-538.
- 10 Kearney, M.R., Wintle, B.A., and Porter, W.P., 2010: Correlative and mechanistic models of species distribution  
11 provide congruent forecasts under climate change. *Conservation Letters*, **3(3)**, 203-213.
- 12 Keenan, T., Maria Serra, J., Lloret, F., Ninyerola, M., and Sabate, S., 2011: Predicting the future of forests in the  
13 Mediterranean under climate change, with niche- and process-based models: CO2 matters! *Global Change*  
14 *Biology*, **17(1)**, 565-579.
- 15 Keith, D.A., Akcakaya, H.R., Thuiller, W., Midgley, G.F., Pearson, R.G., Phillips, S.J., Regan, H.M., Araujo, M.B.,  
16 and Rebelo, T.G., 2008: Predicting extinction risks under climate change: coupling stochastic population  
17 models with dynamic bioclimatic habitat models. *Biology Letters*, **4(5)**, 560-563.
- 18 Kelly, A.E., and Goulden, M.L., 2008: Rapid shifts in plant distribution with recent climate change. *Proceedings of*  
19 *the National Academy of Sciences of the United States of America*, **105(33)**, 11823-11826.
- 20 Ketola, T., Kellermann, V., Kristensen, T.N., and Loeschcke, V., 2012: Constant, cycling, hot and cold thermal  
21 environments: strong effects on mean viability but not on genetic estimates. *Journal of Evolutionary Biology*,  
22 **25(6)**, 1209-1215.
- 23 Kgope, B.S., Bond, W.J., and Midgley, G.F., 2010: Growth responses of African savanna trees implicate  
24 atmospheric [CO<sub>2</sub>] as a driver of past and current changes in savanna tree cover. *Austral Ecology*, **35(4)**, 451-  
25 463.
- 26 Kharuk, V.I., Ranson, K.J., Oskorbin, P.A., Im, S.T., and Dvinskaya, M.L., 2013: Climate induced birch mortality in  
27 Trans-Baikal lake region, Siberia. *Forest Ecology and Management*, **289(0)**, 385-392.
- 28 Khoury, C., Laliberte, B., and Guarino, L., 2010: Trends in ex situ conservation of plant genetic resources: a review  
29 of global crop and regional conservation strategies. *Genetic Resources and Crop Evolution*, **57(4)**, 625-639.
- 30 Kiesecker, J.M., 2011: Global stressors and the global decline of amphibians: tipping the stress immunocompetency  
31 axis. *Ecological Research*, **26(5)**, 897-908.
- 32 Kindermann, G.E., McCallum, I., Fritz, S., and et al., 2008: A global forest growing stock, biomass and carbon map  
33 based on FAO statistics. *Silva Fennica*, **42(3)**, 387-396.
- 34 Kinlan, B.P., and Gaines, S.D., 2003: Propagule dispersal in marine and terrestrial environments: A community  
35 perspective. *Ecology*, **84(8)**, 2007-2020.
- 36 Kint, V., Aertsen, W., Campioli, M., Vansteenckiste, D., Delcloo, A., and Muys, B., 2012: Radial growth change of  
37 temperate tree species in response to altered regional climate and air quality in the period 1901-2008. *Climatic*  
38 *Change*, **115(2)**, 343-363.
- 39 Kirilyanov, A.V., Hagedorn, F., Knorre, A.A., Fedotova, E.V., Vaganov, E.A., Naurzbaev, M.M., Moiseev, P.A.,  
40 and Rigling, A., 2012: 20th century tree-line advance and vegetation changes along an altitudinal transect in the  
41 Putorana Mountains, northern Siberia. *Boreas*, **41(1)**, 56-67.
- 42 Kirilenko, A.P., and Sedjo, R.A., 2007: Climate change impacts on forestry. *Proceedings of the National Academy*  
43 *of Sciences of the United States of America*, **104(50)**, 19697-19702.
- 44 Kirschbaum, M.U.F., 2004: Soil respiration under prolonged soil warming: are rate reductions caused by  
45 acclimation or substrate loss? *Global Change Biology*, **10(11)**, 1870-1877.
- 46 Kirschbaum, M.U.F., Saggar, S., Tate, K.R., Giltrap, D.L., Ausseil, A.-G.E., Greenhalgh, S., and Whitehead, D.,  
47 2012: Comprehensive evaluation of the climate-change implications of shifting land use between forest and  
48 grassland: New Zealand as a case study. *Agriculture, Ecosystems & Environment*, **150**, 123-138.
- 49 Kirwan, M.L., and Blum, L.K., 2011: Enhanced decomposition offsets enhanced productivity and soil carbon  
50 accumulation in coastal wetlands responding to climate change. *Biogeosciences*, **8(4)**, 987-993.
- 51 Klausmeyer, K.R., and Shaw, M.R., 2009: Climate Change, Habitat Loss, Protected Areas and the Climate  
52 Adaptation Potential of Species in Mediterranean Ecosystems Worldwide. *PLoS One*, **4(7)**, 1-9.
- 53 KleinGoldewijk, K., 2001: Estimating global land use change over the past 300 years: The HYDE database. *Global*  
54 *Biogeochemical Cycles*, **5(2)**, 417-433.

- 1 Klingberg, J., Engardt, M., Uddling, J., Karlsson, P.E., and Pleijel, H., 2011: Ozone risk for vegetation in the future  
2 climate of Europe based on stomatal ozone uptake calculations. *Tellus Series a-Dynamic Meteorology and*  
3 *Oceanography*, **63(1)**, 174-187.
- 4 Klos, R.J., Wang, G.G., Bauerle, W.L., and Rieck, J.R., 2009: Drought impact on forest growth and mortality in the  
5 southeast USA: an analysis using Forest Health and Monitoring data. *Ecological Applications*, **19(3)**, 699-708.
- 6 Knapp, A.K., Beier, C., Briske, D.D., Classen, A.T., Luo, Y., Reichstein, M., Smith, M.D., Smith, S.D., Bell, J.E.,  
7 Fay, P.A., Heisler, J.L., Leavitt, S.W., Sherry, R., Smith, B., and Weng, E., 2008a: Consequences of More  
8 Extreme Precipitation Regimes for Terrestrial Ecosystems. *Bioscience*, **58(9)**, 811-821.
- 9 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  
10 encroachment in North American grasslands: shifts in growth form dominance rapidly alters control of  
11 ecosystem carbon inputs. *Global Change Biology*, **14(3)**, 615-623.
- 12 Knapp, S., Kühn, I., Wittig, R., Ozinga, W.A., Poschlod, P., and Klotz, S., 2008b: Urbanization causes shifts in  
13 species' trait state frequencies. *Preslia*, **80(4)**, 375-388.
- 14 Knohl, A., and Baldocchi, D.D., 2008: Effects of diffuse radiation on canopy gas exchange processes in a forest  
15 ecosystem. *Journal of Geophysical Research*, **113(G02023)**.
- 16 Knops, J.M.H., Naemw, S., and Reich, P.B., 2007: The impact of elevated CO<sub>2</sub>, increased nitrogen availability and  
17 biodiversity on plant tissue quality and decomposition. *Global Change Biology*, **13(9)**, 1960-1971.
- 18 Knorr, W., Prentice, I.C., House, J.I., and Holland, E.A., 2005: Long-term sensitivity of soil carbon turnover to  
19 warming. *Nature*, **433(7023)**, 298-301.
- 20 Knox, R., Bisht, G., Wang, J., and Bras, R., 2011: Precipitation Variability over the Forest-to-Nonforest Transition  
21 in Southwestern Amazonia. *Journal of Climate*, **24**, 2368-2377.
- 22 Knudsen, E., Linden, A., Both, C., Jonzen, N., Pulido, F., Saino, N., Sutherland, W.J., Bach, L.A., Coppack, T.,  
23 Ergon, T., Gienapp, P., Gill, J.A., Gordo, O., Hedenstroom, A., Lehikoinen, E., Marra, P.P., Moller, A.P.,  
24 Nilsson, A.L.K., Peron, G., Ranta, E., Rubolini, D., Sparks, T.H., Spina, F., Studds, C.E., Saether, S.A.,  
25 Tryjanowski, P., and Stenseth, N.C., 2011: Challenging claims in the study of migratory birds and climate  
26 change. *Biological Reviews*, **86(4)**, 928-946.
- 27 Knutti, R., and Sedlacek, J., 2012: Robustness and uncertainties in the new CMIP5 climate model projections.  
28 *Nature Clim. Change*, **advance online publication**.
- 29 Koehler, I.H., Poulton, P.R., Auerswald, K., and Schnyder, H., 2010: Intrinsic water-use efficiency of temperate  
30 seminatural grassland has increased since 1857: an analysis of carbon isotope discrimination of herbage from  
31 the Park Grass Experiment. *Global Change Biology*, **16(5)**, 1531-1541.
- 32 Konarzewski, T.K., Murray, B.R., and Godfree, R.C., 2012: Rapid Development of Adaptive, Climate-Driven Clinal  
33 Variation in Seed Mass in the Invasive Annual Forb *Echium plantagineum* L. *PLoS One*, **7(12)**.
- 34 Kongstad, J., Schmidt, I.K., Riis-Nielsen, T., Arndal, M.F., Mikkelsen, T.N., and Beier, C., 2012: High Resilience in  
35 Heathland Plants to Changes in Temperature, Drought, and CO<sub>2</sub> in Combination: Results from the CLIMAITE  
36 Experiment. *Ecosystems*, **15(2)**, 269-283.
- 37 Körner, C., Asshoff, R., Bignucolo, O., Hattenschwiler, S., Keel, S.G., Pelaez-Riedl, S., Pepin, S., Siegwolf,  
38 R.T.W., and Zotz, G., 2005: Carbon flux and growth in mature deciduous forest trees exposed to elevated CO<sub>2</sub>.  
39 *Science*, **309(5739)**, 1360-1362.
- 40 Körner, C., and Basler, D., 2010: Phenology Under Global Warming. *Science*, **327(5972)**, 1461-1462.
- 41 Körner, C., Morgan, J.A., and Norby, R., 2007: CO<sub>2</sub> fertilisation: when, where, how much? In *Terrestrial*  
42 *ecosystems in a changing world* [S. G. Canadell, D. E. Pataki & L. F. Pitelka (eds.)]. Springer, Berlin  
43 Heidelberg, pp. 9-22.
- 44 Koutavas, A., 2008: Late 20th century growth acceleration in greek firs (*Abies cephalonica*) from Cephalonia Island,  
45 Greece: A CO<sub>2</sub> fertilization effect? *Dendrochronologia*, **26(1)**, 13-19.
- 46 Kovach-Orr, C., and Fussmann, G.F., 2013: Evolutionary and plastic rescue in multitrophic model communities.  
47 *Philosophical Transactions of the Royal Society B-Biological Sciences*, **368(1610)**.
- 48 Kraft, N.J.B., Metz, M.R., Condit, R.S., and Chave, J., 2010: The relationship between wood density and mortality  
49 in a global tropical forest data set. *New Phytologist*, **188(4)**, 1124-1136.
- 50 Kramer, K., Bijlsma, R.J., Hickler, T., and Thuiller, W., 2012: Why Would Plant Species Become Extinct Locally If  
51 Growing Conditions Improve? *International Journal of Biological Sciences*, **8(8)**, 1121-1129.
- 52 Kramer, K., Degen, B., Buschbom, J., Hickler, T., Thuiller, W., Sykes, M.T., and de Winter, W., 2010: Modelling  
53 exploration of the future of European beech (*Fagus sylvatica* L.) under climate change-Range, abundance,  
54 genetic diversity and adaptive response. *Forest Ecology and Management*, **259(11)**, 2213-2222.

- 1 Kremer, A., Ronce, O., Robledo-Arnuncio, J.J., Guillaume, F., Bohrer, G., Nathan, R., Bridle, J.R., Gomulkiewicz,  
2 R., Klein, E.K., Ritland, K., Kuparinen, A., Gerber, S., and Schueler, S., 2012: Long-distance gene flow and  
3 adaptation of forest trees to rapid climate change. *Ecology Letters*, **15(4)**, 378-392.
- 4 Krieglner, E., Hall, J.W., Held, H., Dawson, R., and Schellnhuber, H.J., 2009: Imprecise probability assessment of  
5 tipping points in the climate system. *Proceedings of the National Academy of Sciences of the United States of*  
6 *America*, **106(13)**, 5041-5046.
- 7 Kropelin, S., Verschuren, D., Lezine, A.M., Eggermont, H., Cocquyt, C., Francus, P., Cazet, J.P., Fagot, M., Rumes,  
8 B., Russell, J.M., Darius, F., Conley, D.J., Schuster, M., von Suchodoletz, H., and Engstrom, D.R., 2008:  
9 Climate-driven ecosystem succession in the Sahara: The past 6000 years. *Science*, **320(5877)**, 765-768.
- 10 Kudo, G., Amagai, Y., Hoshino, B., and Kaneko, M., 2011: Invasion of dwarf bamboo into alpine snow-meadows in  
11 northern Japan: pattern of expansion and impact on species diversity. *Ecology and Evolution*, **1(1)**, 85-96.
- 12 Kukowski, K., Schwinning, S., and Schwartz, B., 2012: Hydraulic responses to extreme drought conditions in three  
13 co-dominant tree species in shallow soil over bedrock. *Oecologia*, 1-12.
- 14 Kuldna, P., Peterson, K., Poltimae, H., and Luig, J., 2009: An application of DPSIR framework to identify issues of  
15 pollinator loss. *Ecological Economics*, **69(1)**, 32-42.
- 16 Kullman, L., and Öberg, L., 2009: Post-Little Ice Age tree line rise and climate warming in the Swedish Scandes: a  
17 landscape ecological perspective. *Journal of Ecology*, **97(3)**, 415-429.
- 18 Kundzewicz, Z.W., Mata, L.J., Arnell, N.W., Döll, P., Kabat, P., Jiménez, B., Miller, K.A., Oki, T., Sen, Z., and  
19 Shiklomanov, I.A., 2007: Freshwater resources and their management. Climate Change 2007: Impacts,  
20 Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the  
21 Intergovernmental Panel on Climate Change. In *Fourth Assessment Report of the Intergovernmental Panel on*  
22 *Climate Change* [M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson (eds.)].  
23 Cambridge University Press, Cambridge, pp. 173-210.
- 24 Kunkel, K.E., Easterling, D.R., Hubbard, K., and Redmond, K., 2004: Temporal variations in frost-free season in the  
25 United States: 1895-2000. *Geophysical Research Letters*, **31(3)**.
- 26 Kuparinen, A., Savolainen, O., and Schurr, F.M., 2010: Increased mortality can promote evolutionary adaptation of  
27 forest trees to climate change. *Forest Ecology and Management*, **259(5)**, 1003-1008.
- 28 Kurz, W.A., Dymond, C.C., Stinson, G., Rampley, G.J., Neilson, E.T., Carroll, A.L., Ebata, T., and Safranyik, L.,  
29 2008: Mountain pine beetle and forest carbon feedback to climate change. *Nature*, **452(7190)**, 987-990.
- 30 Kusano, T., and Inoue, M., 2008: Long-Term Trends toward Earlier Breeding of Japanese Amphibians. *Journal of*  
31 *Herpetology*, **42(4)**, 608-614.
- 32 Kuussaari, M., Bommarco, R., Heikkinen, R.K., Helm, A., Krauss, J., Lindborg, R., Ockinger, E., Partel, M., Pino,  
33 J., Roda, F., Stefanescu, C., Teder, T., Zobel, M., and Steffan-Dewenter, I., 2009: Extinction debt: a challenge  
34 for biodiversity conservation. *Trends in Ecology & Evolution*, **24(10)**, 564-571.
- 35 Kvalevåg, M.M., and Myhre, G., 2007: Human Impact on Direct and Diffuse Solar Radiation during the Industrial  
36 Era. *Journal of Climate*, **20(19)**, 4874-4883.
- 37 La Sorte, F.A., and Jetz, W., 2010: Avian distributions under climate change: towards improved projections. *Journal*  
38 *of Experimental Biology*, **213(6)**, 862-869.
- 39 Lambert, A.M., Miller-Rushing, A.J., and Inouye, D.W., 2010: Changes in Snowmelt Date and Summer  
40 Precipitation Affect the Flowering Phenology of *Erythronium Grandiflorum* (Glacier Lily; Liliaceae). *American*  
41 *Journal of Botany*, **97(9)**, 1431-1437.
- 42 Lambin, E.F., and Meyfroidt, P., 2011: Global land use change, economic globalization, and the looming land  
43 scarcity. *Proceedings of the National Academy of Sciences of the United States of America*, **108(9)**, 3465-3472.
- 44 Lane, J.E., Kruuk, L.E.B., Charmantier, A., Murie, J.O., and Dobson, F.S., 2012: Delayed phenology and reduced  
45 fitness associated with climate change in a wild hibernator. *Nature*, **489(7417)**, 554.
- 46 Langan, S.J., Johnston, L., Donaghy, M.J., Youngson, A.F., Hay, D.W., and Soulsby, C., 2001: Variation in river  
47 water temperatures in an upland stream over a 30-year period. *Science of the Total Environment*, **265(1-3)**, 195-  
48 207.
- 49 Langley, J.A., and Magonigal, J.P., 2010: Ecosystem response to elevated CO(2) levels limited by nitrogen-induced  
50 plant species shift. *Nature*, **466(7302)**, 96-99.
- 51 Lantz, T.C., Gergel, S.E., and Henry, G.H.R., 2010: Response of green alder (*Alnus viridis* subsp. *fruticosa*) patch  
52 dynamics and plant community composition to fire and regional temperature in north-western Canada. *Journal*  
53 *of Biogeography*, **37(8)**, 1597-1610.

- 1 Lantz, T.C., Kokelj, S.V., Gergel, S.E., and Henry, G.H.R., 2009: Relative impacts of disturbance and temperature:  
2 persistent changes in microenvironment and vegetation in retrogressive thaw slumps. *Global Change Biology*,  
3 **15(7)**, 1664-1675.
- 4 Lapola, D.M., Oyama, M.D., and Nobre, C.A., 2009: Exploring the range of climate biome projections for tropical  
5 South America: The role of CO<sub>2</sub> fertilization and seasonality. *Global Biogeochem. Cycles*, **23(3)**, GB3003.
- 6 Lapola, D.M., Schaldach, R., Alcamo, J., Bondeau, A., Koch, J., Koelking, C., and Priess, J.A., 2010: Indirect land-  
7 use changes can overcome carbon savings from biofuels in Brazil. *Proceedings of the National Academy of*  
8 *Sciences of the United States of America*, **107(8)**, 3388-3393.
- 9 Larsen, K.S., Andresen, L.C., Beier, C., Jonasson, S., Albert, K.R., Ambus, P., Arndal, M.F., Carter, M.S.,  
10 Christensen, S., Holmstrup, M., Ibrom, A., Kongstad, J., van der Linden, L., Maraldo, K., Michelsen, A.,  
11 Mikkelsen, T.N., Pilegaard, K., Prieme, A., Ro-Poulsen, H., Schmidt, I.K., Selsted, M.B., and Stevnbak, K.,  
12 2011: Reduced N cycling in response to elevated CO<sub>2</sub>, warming, and drought in a Danish heathland:  
13 Synthesizing results of the CLIMAITE project after two years of treatments. *Global Change Biology*, **17(5)**,  
14 1884-1899.
- 15 Laurance, W.F., Useche, D.C., Shoo, L.P., Herzog, S.K., Kessler, M., Escobar, F., Brehm, G., Axmacher, J.C.,  
16 Chen, I.C., Gamez, L.A., Hietz, P., Fiedler, K., Pyrcz, T., Wolf, J., Merkord, C.L., Cardelus, C., Marshall, A.R.,  
17 Ah-Peng, C., Aplet, G.H., Arizmendi, M.D., Baker, W.J., Barone, J., Bruhl, C.A., Busmann, R.W., Cicuzza,  
18 D., Eilu, G., Favila, M.E., Hemp, A., Hemp, C., Homeier, J., Hurtado, J., Jankowski, J., Kattan, G., Kluge, J.,  
19 Kromer, T., Lees, D.C., Lehnert, M., Longino, J.T., Lovett, J., Martin, P.H., Patterson, B.D., Pearson, R.G.,  
20 Peh, K.S.H., Richardson, B., Richardson, M., Samways, M.J., Senbeta, F., Smith, T.B., Utteridge, T.M.A.,  
21 Watkins, J.E., Wilson, R., Williams, S.E., and Thomas, C.D., 2011: Global warming, elevational ranges and the  
22 vulnerability of tropical biota. *Biological Conservation*, **144(1)**, 548-557.
- 23 Lavergne, S., Evans, M.E.K., Burfield, I.J., Jiguet, F., and Thuiller, W., 2013: Are species' responses to global  
24 change predicted by past niche evolution? *Philosophical Transactions of the Royal Society B: Biological*  
25 *Sciences*, **368(1610)**.
- 26 Lavergne, S., Mouquet, N., Thuiller, W., and Ronce, O., 2010: Biodiversity and Climate Change: Integrating  
27 Evolutionary and Ecological Responses of Species and Communities. *Annual Review of Ecology, Evolution,*  
28 *and Systematics, Vol 41*, **41**, 321-350.
- 29 Lawrence, D.M., and Swenson, S.C., 2011: Permafrost response to increasing Arctic shrub abundance depends on  
30 the relative influence of shrubs on local soil cooling versus large-scale climate warming. *Environmental*  
31 *Research Letters*, **6(4)**.
- 32 Lawrence, D.M., Thornton, P.E., Oleson, K.W., and Bonan, G.B., 2007: The Partitioning of Evapotranspiration into  
33 Transpiration, Soil Evaporation, and Canopy Evaporation in a GCM: Impacts on Land-Atmosphere Interaction.  
34 *Journal of Hydrometeorology*, **8**, 862-880.
- 35 Lawson, C.R., Bennie, J.J., Thomas, C.D., Hodgson, J.A., and Wilson, R.J., 2012: Local and landscape management  
36 of an expanding range margin under climate change. *Journal of Applied Ecology*, **49**, 552-561.
- 37 Le Conte, Y., and Navajas, M., 2008: Climate change: impact on honey bee populations and diseases. *Revue*  
38 *Scientifique Et Technique-Office International Des Epizooties*, **27(2)**, 499-510.
- 39 Le Quere, C., Raupach, M.R., Canadell, J.G., and Marland, G., 2009: Trends in the sources and sinks of carbon  
40 dioxide. *Nature Geoscience*, **2(12)**, 831-836.
- 41 Leadley, P., Periera, H.N., Alkemade, R., Fernandez-Manjarres, J.F., Proenca, V., Scharlemann, J.P.W., and  
42 Walpole, M.J., 2010: *Biodiversity Scenarios: Projections of 21st century change in biodiversity and associated*  
43 *ecosystem services*. Technical series Series 50, Montreal, 132 pp.
- 44 Leakey, A.D.B., Ainsworth, E.A., Bernacchi, C.J., Rogers, A., Long, S.P., and Ort, D.R., 2009: Elevated CO<sub>2</sub>  
45 effects on plant carbon, nitrogen, and water relations: six important lessons from FACE. *Journal of*  
46 *Experimental Botany*, **60(10)**, 2859-2876.
- 47 Leal, M., and Gunderson, A.R., 2012: Rapid Change in the Thermal Tolerance of a Tropical Lizard. *American*  
48 *Naturalist*, **180(6)**, 815-822.
- 49 Lee, M., Manning, P., Rist, J., Power, S.A., and Marsh, C., 2010: A global comparison of grassland biomass  
50 responses to CO<sub>2</sub> and nitrogen enrichment. *Philosophical Transactions of the Royal Society B-Biological*  
51 *Sciences*, **365(1549)**, 2047-2056.
- 52 Leishman, M.R., Haslehurst, T., Ares, A., and Baruch, Z., 2007: Leaf trait relationships of native and invasive  
53 plants: community- and global-scale comparisons. *New Phytologist*, **176(3)**, 635-643.

- 1 Lenoir, J., Gegout, J.C., Dupouey, J.L., Bert, D., and Svenning, J.C., 2010: Forest plant community changes during  
2 1989-2007 in response to climate warming in the Jura Mountains (France and Switzerland). *Journal of*  
3 *Vegetation Science*, **21(5)**, 949-964.
- 4 Lenoir, J., Gegout, J.C., Marquet, P.A., de Ruffray, P., and Brisse, H., 2008: A significant upward shift in plant  
5 species optimum elevation during the 20th century. *Science*, **320(5884)**, 1768-1771.
- 6 Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S., and Schellnhuber, H.J., 2008: Tipping  
7 elements in the Earth's climate system. *Proceedings of the National Academy of Sciences of the United States of*  
8 *America*, **105(6)**, 1786-1793.
- 9 Leonelli, G., Pelfini, M., Morra di Cella, U., and Garavaglia, V., 2011: Climate Warming and the Recent Treeline  
10 Shift in the European Alps: The Role of Geomorphological Factors in High-Altitude Sites. *AMBIO: A Journal*  
11 *of the Human Environment*, **40(3)**, 264-273.
- 12 Leuning, R., 1995: A critical appraisal of a combined stomatal-photosynthesis  
13 model for C3 plants. *Plant, Cell and Environment*, **18**, 339-355.
- 14 Leuzinger, S., and Körner, C., 2010: Rainfall distribution is the main driver of runoff under future CO<sub>2</sub>-  
15 concentration in a temperate deciduous forest. *Global Change Biology*, **16(1)**, 246-254.
- 16 Leuzinger, S., Luo, Y.Q., Beier, C., Dieleman, W., Vicca, S., and Korner, C., 2011: Do global change experiments  
17 overestimate impacts on terrestrial ecosystems? *Trends in Ecology & Evolution*, **26(5)**, 236-241.
- 18 Levis, S., 2010: Modeling vegetation and land use in models of the Earth System. *Wiley Interdisciplinary Reviews:*  
19 *Climate Change*, **1(6)**, 840-856.
- 20 Lewis, S.L., Brando, P.M., Phillips, O.L., van der Heijden, G.M.F., and Nepstad, D., 2011: The 2010 Amazon  
21 Drought. *Science*, **331(6017)**, 554-554.
- 22 Lewis, S.L., Lloyd, J., Sitch, S., Mitchard, E.T.A., and Laurance, W.F., 2009a: Changing Ecology of Tropical  
23 Forests: Evidence and Drivers. *Annual Review of Ecology Evolution and Systematics*, **40**, 529-549.
- 24 Lewis, S.L., Lopez-Gonzalez, G., Sonke, B., Affum-Baffoe, K., Baker, T.R., Ojo, L.O., Phillips, O.L., Reitsma,  
25 J.M., White, L., Comiskey, J.A., Djuikouo, M.N., Ewango, C.E.N., Feldpausch, T.R., Hamilton, A.C., Gloor,  
26 M., Hart, T., Hladik, A., Lloyd, J., Lovett, J.C., Makana, J.R., Malhi, Y., Mbago, F.M., Ndangalasi, H.J.,  
27 Peacock, J., Peh, K.S.H., Sheil, D., Sunderland, T., Swaine, M.D., Taplin, J., Taylor, D., Thomas, S.C., Votere,  
28 R., and Wöll, H., 2009b: Increasing carbon storage in intact African tropical forests. *Nature*, **457**, 1003-1007.
- 29 Li, D.Z., and Pritchard, H.W., 2009: The science and economics of ex situ plant conservation. *Trends in Plant*  
30 *Science*, **14(11)**, 614-621.
- 31 Li, W.H., Dickinson, R.E., Fu, R., Niu, G.Y., Yang, Z.L., and Canadell, J.G., 2007: Future precipitation changes and  
32 their implications for tropical peatlands. *Geophysical Research Letters*, **34(L01403)**, 1-6.
- 33 Li, Z., Liu, W.-z., Zhang, X.-c., and Zheng, F.-l., 2009: Impacts of land use change and climate variability on  
34 hydrology in an agricultural catchment on the Loess Plateau of China. *Journal of Hydrology*, **377(1-2)**, 35-42.
- 35 Liao, J.D., Boutton, T.W., and Jastrow, J.D., 2006: Storage and dynamics of carbon and nitrogen in soil physical  
36 fractions following woody plant invasion of grassland. *Soil Biology and Biochemistry*, **38(11)**, 3184-3196.
- 37 Liljedahl, A., Hinzman, L., Busey, R., and Yoshikawa, K., 2007: Physical short-term changes after a tussock tundra  
38 fire, Seward Peninsula, Alaska. *J. Geophys. Res.*, **112(F2)**, F02S07.
- 39 Lima, I.B.T., Ramos, F.M., Bambace, L.A.W., and Rosa, R.R., 2008: Methane Emissions from Large Dams as  
40 Renewable Energy Resources: A Developing Nation Perspective. . *Mitigation and Adaptation Strategies for*  
41 *Global Change*, **13**, 193-206.
- 42 Limpens, J., Berendse, F., Blodau, C., Canadell, J.G., Freeman, C., Holden, J., Roulet, N., Rydin, H., and  
43 Schaeppman-Strub, G., 2008: Peatlands and the carbon cycle: from local processes to global implications - a  
44 synthesis. *Biogeosciences*, **5(5)**, 1475-1491.
- 45 Limpens, J., Granath, G., Gunnarsson, U., Aerts, R., Bayley, S., Bragazza, L., Bubier, J., Buttler, A., van den Berg,  
46 L.J.L., Francez, A.J., Gerdol, R., Grosvernier, P., Heijmans, M., Hoosbeek, M.R., Hotes, S., Ilomets, M., Leith,  
47 I., Mitchell, E.A.D., Moore, T., Nilsson, M.B., Nordbakken, J.F., Rochefort, L., Rydin, H., Sheppard, L.J.,  
48 Thormann, M., Wiedermann, M.M., Williams, B.L., and Xu, B., 2011: Climatic modifiers of the response to  
49 nitrogen deposition in peat-forming Sphagnum mosses: a meta-analysis. *New Phytologist*, **191(2)**, 496-507.
- 50 Linares, J.C., Camarero, J.J., and Carreira, J.A., 2009: Interacting effects of changes in climate and forest cover on  
51 mortality and growth of the southernmost European fir forests. *Global Ecology and Biogeography*, **18(4)**, 485-  
52 497.



- 1 Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S.,  
2 Corona, P., Kolstrom, M., Lexer, M.J., and Marchetti, M., 2010: Climate change impacts, adaptive capacity,  
3 and vulnerability of European forest ecosystems. *Forest Ecology and Management*, **259(4)**, 698-709.
- 4 Lips, K.R., Diffendorfer, J., Mendelson, J.R., and Sears, M.W., 2008: Riding the wave: Reconciling the roles of  
5 disease and climate change in amphibian declines. *Plos Biology*, **6(3)**, 441-454.
- 6 Littell, J.S., McKenzie, D., Peterson, D.L., and Westerling, A.L., 2009: Climate and wildfire area burned in western  
7 U.S. ecoprovinces, 1916–2003. *Ecological Applications*, **19**, 1003-1021.
- 8 Littell, J.S., Oneil, E.E., McKenzie, D., Hicke, J.A., Lutz, J.A., Norheim, R.A., and Elsner, M.M., 2010: Forest  
9 ecosystems, disturbance, and climatic change in Washington State, USA. *Climatic Change*, **102(1-2)**, 129-158.
- 10 Liu, H., Allen, C., Guo, D., Williams, A.P., Wu, X., Anenkhonov, O.A., Liang, E., Sandanov, D.V., Badmaeva,  
11 N.K., and Yin, Y., in revision: Rapid growing season warming accelerates tree growth decline in semi-arid  
12 forests of Inner Asia. *Global Change Biology*.
- 13 Liu, W., Zhang, Z., and Wan, S., 2009: Predominant role of water in regulating soil and microbial respiration and  
14 their responses to climate change in a semiarid grassland. *Global Change Biology*, **15(1)**, 184-195.
- 15 Lloyd, A.H., Bunn, A.G., and Berner, L., 2011: A latitudinal gradient in tree growth response to climate warming in  
16 the Siberian taiga. *Global Change Biology*, **17(5)**, 1935-1945.
- 17 Lloyd, A.H., and Fastie, C.L., 2003: Recent changes in tree line forest distribution and structure in interior Alaska.  
18 *Ecoscience*, **10**, 176-185.
- 19 Lloyd, J., and Farquhar, G.D., 2008: Effects of rising temperatures and [CO<sub>2</sub>] on the physiology of tropical forest  
20 trees. *Philosophical Transactions of the Royal Society B-Biological Sciences*, **363(1498)**, 1811-1817.
- 21 Loader, N.J., Walsh, R.P.D., Robertson, I., Bidin, K., Ong, R.C., Reynolds, G., McCarroll, D., Gagen, M., and  
22 Young, G.H.F., 2011: Recent trends in the intrinsic water-use efficiency of ringless rainforest trees in Borneo.  
23 *Philosophical Transactions of the Royal Society B: Biological Sciences*, **366(1582)**, 3330-3339.
- 24 Loarie, S.R., Duffy, P.B., Hamilton, H., Asner, G.P., Field, C.B., and Ackerly, D.D., 2009: The velocity of climate  
25 change. *Nature*, **462(7276)**, 1052-U1111.
- 26 Loarie, S.R., Lobell, D.B., Asner, G.P., Mu, Q., and Field, C.B., 2011: Direct impacts on local climate of sugar-cane  
27 expansion in Brazil. *Nature Climate Change*, **1(2)**, 105-109.
- 28 Lobell, D.B., Schlenker, W., and Costa-Roberts, J., 2011: Climate Trends and Global Crop Production Since 1980.  
29 *Science*, **333(6042)**, 616-620.
- 30 Long, S.P., Ainsworth, E.A., Rogers, A., and Ort, D.R., 2004: Rising atmospheric carbon dioxide: plants FACE the  
31 future. *Annual Review of Plant Biology*, **55(1)**, 591-628.
- 32 Lorenzen, E.D., Nogues-Bravo, D., Orlando, L., Weinstock, J., Binladen, J., Marske, K.A., Ugan, A., Borregaard,  
33 M.K., Gilbert, M.T.P., Nielsen, R., Ho, S.Y.W., Goebel, T., Graf, K.E., Byers, D., Stenderup, J.T., Rasmussen,  
34 M., Campos, P.F., Leonard, J.A., Koepfli, K.P., Froese, D., Zazula, G., Stafford, T.W., Aaris-Sorensen, K.,  
35 Batra, P., Haywood, A.M., Singarayer, J.S., Valdes, P.J., Boeskorov, G., Burns, J.A., Davydov, S.P., Haile, J.,  
36 Jenkins, D.L., Kosintsev, P., Kuznetsova, T., Lai, X.L., Martin, L.D., McDonald, H.G., Mol, D., Meldgaard,  
37 M., Munch, K., Stephan, E., Sablin, M., Sommer, R.S., Sipko, T., Scott, E., Suchard, M.A., Tikhonov, A.,  
38 Willerslev, R., Wayne, R.K., Cooper, A., Hofreiter, M., Sher, A., Shapiro, B., Rahbek, C., and Willerslev, E.,  
39 2011: Species-specific responses of Late Quaternary megafauna to climate and humans. *Nature*, **479(7373)**,  
40 359-U195.
- 41 Loss, S.R., Terwilliger, L.A., and Peterson, A.C., 2011: Assisted colonization: Integrating conservation strategies in  
42 the face of climate change. *Biological Conservation*, **144(1)**, 92-100.
- 43 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  
44 on China's terrestrial carbon uptake in the context of multifactor environmental changes. *Ecological*  
45 *Applications*, **22(1)**, 53-75.
- 46 Lu, J., Deser, C., and Reichler, T., 2009: Cause of the widening of the tropical belt since 1958. *Geophysical*  
47 *Research Letters*, **36**.
- 48 Luckman, B., and Kavanagh, T., 2000: Impact of Climate Fluctuations on Mountain Environments in the Canadian  
49 Rockies. *AMBIO: A Journal of the Human Environment*, **29(7)**, 371-380.
- 50 Lunt, I.D., Winsemius, L.M., McDonald, S.P., Morgan, J.W., and Dehaan, R.L., 2010: How widespread is woody  
51 plant encroachment in temperate Australia? Changes in woody vegetation cover in lowland woodland and  
52 coastal ecosystems in Victoria from 1989 to 2005. *Journal of Biogeography*, **37(4)**, 722-732.
- 53 Luo, Y., Wan, S., Hui, D., and Wallace, L., 2001: Acclimatization of soil respiration to warming in a tall grass  
54 prairie. *Nature*, **413(6856)**, 622-625.

- 1 Luo, Y.Q., Gerten, D., Le Maire, G., Parton, W.J., Weng, E.S., Zhou, X.H., Keough, C., Beier, C., Ciais, P., Cramer,  
2 W., Dukes, J.S., Emmett, B., Hanson, P.J., Knapp, A., Linder, S., Nepstad, D., and Rustad, L., 2008: Modeled  
3 interactive effects of precipitation, temperature, and [CO<sub>2</sub>] on ecosystem carbon and water dynamics in  
4 different climatic zones. *Global Change Biology*, **14**(9), 1986-1999.
- 5 Luyssaert, S., Ciais, P., Piao, S.L., Schulze, E.D., Jung, M., Zaehle, S., Schelhaas, M.J., Reichstein, M., Churkina,  
6 G., Papale, D., Abril, G., Beer, C., Grace, J., Loustau, D., Matteucci, G., Marnani, F., Nabuurs, G.J., Verbeeck,  
7 H., Sulkava, M., Van Der Werf, G.R., Janssens, I.A., and Members of the Carboeurope, I.P.S.T., 2010: The  
8 European carbon balance. Part 3: forests. *Global Change Biology*, **16**(5), 1429-1450.
- 9 Lydeard, C., Cowie, R.H., Ponder, W.F., Bogan, A.E., Bouchet, P., Clark, S.A., Cummings, K.S., Frest, T.J.,  
10 Gargominy, O., Herbert, D.G., Hershler, R., Perez, K.E., Roth, B., Seddon, M., Strong, E.E., and Thompson,  
11 F.G., 2004: The global decline of nonmarine mollusks. *Bioscience*, **54**(4), 321-330.
- 12 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  
13 and Nitrogen Addition on Soil Nitrogen Cycling in a Temperate Grassland, Northeastern China. *PLoS One*,  
14 **6**(11), 1-8.
- 15 Ma, T., and Zhou, C.G., 2012: Climate-associated changes in spring plant phenology in China. *International*  
16 *Journal of Biometeorology*, **56**(2), 269-275.
- 17 Ma, Z., Peng, C., Zhu, Q., Chen, H., Yu, G., Li, W.H., Zhou, X., Wang, W., and Zhang, W., 2012: Regional  
18 drought-induced reduction in the biomass carbon sink of Canada's boreal forests. *Proceedings of the National*  
19 *Academy of Sciences*, **109**(7), 2423-2427.
- 20 MacArthur, A.G., 1973: *Grassland fire danger meter Mk I (published as a circular slide rule)*. Canberra,pp.
- 21 MacDonald, G.M., 2010: Global warming and the Arctic: a new world beyond the reach of the Grinnellian niche?  
22 *The Journal of Experimental Biology*, **213**, 855-861.
- 23 MacDonald, G.M., Bennett, K.D., Jackson, S.T., Parducci, L., Smith, F.A., Smol, J.P., and Willis, K.J., 2008:  
24 Impacts of climate change on species, populations and communities: palaeobiogeographical insights and  
25 frontiers. *Progress In Physical Geography*, **32**(2), 139-172.
- 26 Macias Fauria, M., and Johnson, E.A., 2008: Climate and wildfires in the North American boreal forest.  
27 *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, **363**(1501), 2317-  
28 2329.
- 29 Mack, M.C., Bret-Harte, M.S., Hollingsworth, T.N., Jandt, R.R., Schuur, E.A.G., Shaver, G.R., and Verbyla, D.L.,  
30 2011: Carbon loss from an unprecedented Arctic tundra wildfire. *Nature*, **475**(7357), 489-492.
- 31 Mack, M.C., Treseder, K.K., Manies, K.L., Harden, J.W., Schuur, E.A.G., Vogel, J.G., Randerson, J.T., and Chapin,  
32 F.S., 2008: Recovery of aboveground plant biomass and productivity after fire in mesic and dry black spruce  
33 forests of interior alaska. *Ecosystems*, **11**(2), 209-225.
- 34 Mackelprang, R., Waldrop, M.P., DeAngelis, K.M., David, M.M., Chavarria, K.L., Blazewicz, S.J., Rubin, E.M.,  
35 and Jansson, J.K., 2011: Metagenomic analysis of a permafrost microbial community reveals a rapid response  
36 to thaw. *Nature*, **480**(7377), 368-U120.
- 37 Maclachlan, J.S., Hellmann, J.J., and Schwarz, M.W., 2007: A Framework for Debate of Assisted Migration in an  
38 Era of Climate Change. *Conservation Biology*, **21**(2), 297-302.
- 39 Magalhães, M.F., Beja, P., Schlosser, I.J., and Collares-Pereira, M.J., 2007: Effects of multi-year droughts on fish  
40 assemblages of seasonally drying Mediterranean streams. *Freshwater Biology*, **52**(8), 1494-1510.
- 41 Magnani, F., Mencuccini, M., Borghetti, M., Berbigier, P., Berninger, F., Delzon, S., Grelle, A., Hari, P., Jarvis,  
42 P.G., Kolari, P., Kowalski, A.S., Lankreijer, H., Law, B.E., Lindroth, A., Loustau, D., Manca, G., Moncrieff,  
43 J.B., Rayment, M., Tedeschi, V., Valentini, R., and Grace, J., 2007: The human footprint in the carbon cycle of  
44 temperate and boreal forests. *Nature*, **447**(7146), 848-850.
- 45 Mainka, S.A., and Howard, G.W., 2010: Climate change and invasive species: double jeopardy. *Integrative Zoology*,  
46 **5**(2), 102-111.
- 47 Malcolm, J.R., Liu, C.R., Neilson, R.P., Hansen, L., and Hannah, L., 2006: Global warming and extinctions of  
48 endemic species from biodiversity hotspots. *Conservation Biology*, **20**(2), 538-548.
- 49 Malhi, Y., Aragao, L., Metcalfe, D.B., Paiva, R., Quesada, C.A., Almeida, S., Anderson, L., Brando, P., Chambers,  
50 J.Q., da Costa, A.C.L., Hutya, L.R., Oliveira, P., Patino, S., Pyle, E.H., Robertson, A.L., and Teixeira, L.M.,  
51 2009a: Comprehensive assessment of carbon productivity, allocation and storage in three Amazonian forests.  
52 *Global Change Biology*, **15**(5), 1255-1274.
- 53 Malhi, Y., Aragao, L.E.O.C., Galbraith, D., Huntingford, C., Fisher, R., Zelazowski, P., Sitch, S., McSweeney, C.,  
54 and Meir, P., 2009b: Exploring the likelihood and mechanism of a climate-change-induced dieback of the

- 1 Amazon rainforest. *Proceedings of the National Academy of Sciences of the United States of America*, **106(49)**,  
2 20610-20615.
- 3 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  
4 ecological perspective. In *Aquatic ecosystems: trends and global prospects*. [N. V. C. Polunin (ed.)]. Cambridge  
5 Press, Cambridge, UK, pp. 19-29.
- 6 Maniatis, D., Malhi, Y., Andre, L.S., Mollicone, D., Barbier, N., Saatchi, S., Henry, M., Tellier, L., Schwartzberg,  
7 M., and White, M., 2011: Evaluating the Potential of Commercial Forest Inventory Data to Report on Forest  
8 Carbon Stock and Forest Carbon Stock Changes for REDD+under the UNFCCC. doi. *International Journal of*  
9 *Forestry Research*, **2011(134526)**, 2-14.
- 10 Mann, D.H., Rupp, T.S., Olson, M.A., and Duffy, P.A., 2012: Is Alaska's Boreal Forest Now Crossing a Major  
11 Ecological Threshold? *Arctic Antarctic and Alpine Research*, **44(3)**, 319-331.
- 12 Maraldo, K., Schmidt, I.K., Beier, C., and Holmstrup, M., 2008: Can field populations of the enchytraeid, *Cognettia*  
13 *sphagnetorum*, adapt to increased drought stress? *Soil Biology & Biochemistry*, **40(7)**, 1765-1771.
- 14 Marengo, J.A., Tomasella, J., Alves, L.M., Soares, W.R., and Rodriguez, D.A., 2011: The drought of 2010 in the  
15 context of historical droughts in the Amazon region. *Geophys. Res. Lett.*, **38(12)**, L12703.
- 16 Marini, L., Ayres, M., Battisti, A., and Faccoli, M., 2012: Climate affects severity and altitudinal distribution of  
17 outbreaks in an eruptive bark beetle. *Climatic Change*, **115(2)**, 327-341.
- 18 Marlon, J.R., Bartlein, P.J., Daniau, A.-L., Harrison, S.P., Maezumi, S.Y., Power, M.J., Tinner, W., and Vanni re,  
19 B., 2013: Global biomass burning: a synthesis and review of Holocene paleofire records and their controls.  
20 *Quaternary Science Reviews*, **65(0)**, 5-25.
- 21 Marlon, J.R., Bartlein, P.J., Walsh, M.K., Harrison, S.P., Brown, K.J., Edwards, M.E., Higuera, P.E., Power, M.J.,  
22 Anderson, R.S., Briles, C., Brunelle, A., Carcaillet, C., Daniels, M., Hu, F.S., Lavoie, M., Long, C., Minckley,  
23 T., Richard, P.J.H., Scott, A.C., Shafer, D.S., Tinner, W., Umbanhowar, C.E., and Whitlock, C., 2009: Wildfire  
24 responses to abrupt climate change in North America. *Proceedings of the National Academy of Sciences of the*  
25 *United States of America*, **106(8)**, 2519-2524.
- 26 Martin, D., Lal, T., Sachdev, C.B., and Sharma, J.P., 2010: Soil organic carbon storage changes with climate  
27 change, landform and land use conditions in Garhwal hills of the Indian Himalayan mountains. *Agriculture,*  
28 *Ecosystems & Environment*, **138(1-2)**, 64-73.
- 29 Martin, T.E., and Maron, J.L., 2012: Climate impacts on bird and plant communities from altered animal-plant  
30 interactions. *Nature Climate Change*, **2(3)**, 195-200.
- 31 Martinez-Alier, J., 2011: The EROI of Agriculture and its use by the Via Campesina. *The Journal of Peasant*  
32 *Studies*, **38(1)**, 145-160.
- 33 Martinez, P.J., 2012: Invasive crayfish in a high desert river: Implications of concurrent invaders and climate  
34 change. *Aquatic Invasions*, **7(2)**, 219-234.
- 35 Maseyk, K., Hemming, D., Angert, A., Leavitt, S.W., and Yakir, D., 2011: Increase in water-use efficiency and  
36 underlying processes in pine forests across a precipitation gradient in the dry Mediterranean region over the past  
37 30 years. *Oecologia*, **167(2)**, 573-585.
- 38 Maslin, M., Owen, M., Betts, R., Day, S., Dunkley Jones, T., and Ridgwell, A., 2010: Gas hydrates: past and future  
39 geohazard? *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering*  
40 *Sciences*, **368(1919)**, 2369-2393.
- 41 Mastrandrea, M.D., Field, C.B., Stocker, T.F., Edenhofer, O., Ebi, K.L., Frame, D.J., Held, H., Kriegler, E., Mach,  
42 K.J., Matschoss, P.R., Plattner, G.-K., Yohe, G.W., and Zwiers, F.W., 2010: *Guidance Note for Lead Authors of*  
43 *the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*. Intergovernmental Panel on  
44 *Climate Change (IPCC)*. Available at <Fehler! Hyperlink-Referenz ung ltig.>, 5 pp.
- 45 Matthews, S.N., Iverson, L.R., Prasad, A.M., Peters, M.P., and Rodewald, P.G., 2011: Modifying climate change  
46 habitat models using tree species-specific assessments of model uncertainty and life history-factors. *Forest*  
47 *Ecology and Management*, **262(8)**, 1460-1472.
- 48 Matthiessen, B., Mielke, E., and Sommer, U., 2010: Dispersal decreases diversity in heterogeneous  
49 metacommunities by enhancing regional competition. *Ecology*, **91(7)**, 2022-2033.
- 50 Mattila, N., Kaitala, V., Komonen, A., Paivinen, J., and Kotiaho, J.S., 2011: Ecological correlates of distribution  
51 change and range shift in butterflies. *Insect Conservation and Diversity*, **4(4)**, 239-246.
- 52 Matusick, G., Ruthrof, K.X., Brouwers, N.C., Dell, B., and Hardy, G.S.J., 2013: Sudden forest canopy collapse  
53 corresponding with extreme drought and heat in a mediterranean-type eucalypt forest in southwestern Australia.  
54 1-14.

- 1 Matusick, G., Ruthrof, K.X., and Hardy, G.S.J., 2012: Drought and Heat Triggers Sudden and Severe Dieback in a  
2 Dominant Mediterranean-Type Woodland Species. *Open Journal of Forestry*, **2(4)**, 183-186.
- 3 Matzek, V., 2012: Trait Values, Not Trait Plasticity, Best Explain Invasive Species' Performance in a Changing  
4 Environment. *PLoS One*, **7(10)**.
- 5 Mayle, F.E., and Power, M.J., 2008: Impact of a drier Early-Mid-Holocene climate upon Amazonian forests.  
6 *Philosophical Transactions of the Royal Society B-Biological Sciences*, **363(1498)**, 1829-1838.
- 7 McAfee, K., 2012: The contradictory logic of global ecosystem services markets. *Development and Change*, **43(1)**,  
8 105-131.
- 9 McAlpine, C.A., Syktus, J., Ryan, J.G., Deo, R.C., Mckeon, G.M., McGowan, H.A., and Phinn, S.R., 2009: A  
10 continent under stress: interactions, feedbacks and risks associated with impact of modified land cover on  
11 Australia's climate. *Global Change Biology*, **15(9)**, 2206-2223.
- 12 McCain, C.M., and Colwell, R.K., 2011: Assessing the threat to montane biodiversity from discordant shifts in  
13 temperature and precipitation in a changing climate. *Ecology Letters*, **14(12)**, 1236-1245.
- 14 McCarthy, H.R., Oren, R., Johnsen, K.H., Gallet-Budynek, A., Pritchard, S.G., Cook, C.W., LaDeau, S.L., Jackson,  
15 R.B., and Finzi, A.C., 2010: Re-assessment of plant carbon dynamics at the Duke free-air CO<sub>2</sub> enrichment site:  
16 interactions of atmospheric [CO<sub>2</sub>] with nitrogen and water availability over stand development. *New*  
17 *Phytologist*, **185(2)**, 514-528.
- 18 McDougall, K.L., Alexander, J.M., Haider, S., Pauchard, A., Walsh, N.G., and Kueffer, C., 2011: Alien flora of  
19 mountains: global comparisons for the development of local preventive measures against plant invasions.  
20 *Diversity and Distributions*, **17(1)**, 103-111.
- 21 McDowell, N.G., Beerling, D.J., Breshears, D.D., Fisher, R.A., Raffa, K.F., and Stitt, M., 2011: The  
22 interdependence of mechanisms underlying climate-driven vegetation mortality. *Trends in Ecology &*  
23 *Evolution*, **26(10)**, 523-532.
- 24 McGeoch, M.A., Butchart, S.H.M., Spear, D., Marais, E., Kleynhans, E.J., Symes, A., Chanson, J., and Hoffmann,  
25 M., 2010: Global indicators of biological invasion: species numbers, biodiversity impact and policy responses.  
26 *Diversity and Distributions*, **16(1)**, 95-108.
- 27 McGuire, A.D., Chapin, F.S., Wirth, C., Apps, M., Bhatti, J., Callaghan, T., Christensen, T.R., Clein, J.S., Fukuda,  
28 M., Maximov, T., Onuchin, A., Shvidenko, A., Vaganov, E., Canadell, J.G., Pataki, D.E., and Pitelka, L.F.,  
29 2007: Responses of high latitude ecosystems to global change: potential consequences for the climate system. In  
30 *Terrestrial Ecosystems in a Changing World*. Springer Berlin Heidelberg, pp. 297-310.
- 31 McGuire, A.D., Christensen, T.R., Hayes, D., Heroult, A., Euskirchen, E., Yi, Y., Kimball, J.S., Koven, C., Lafleur,  
32 P., Miller, P.A., Oechel, W., Peylin, P., and Williams, M., 2012: An assessment of the carbon balance of arctic  
33 tundra: comparisons among observations, process models, and atmospheric inversions. *Biogeosciences*  
34 *Discuss.*, **9(4)**, 4543-4594.
- 35 McGuire, A.D., Hayes, D.J., Kicklighter, D.W., Manizza, M., Zhuang, Q., Chen, M., Follows, M.J., Gurney, K.R.,  
36 McClelland, J.W., Melillo, J.M., Peterson, B.J., and Prinn, R.G., 2010: An analysis of the carbon balance of the  
37 Arctic Basin from 1997 to 2006. *Tellus Series B-Chemical and Physical Meteorology*, **62(5)**, 455-474.
- 38 McKenzie, V.J., and Peterson, A.C., 2012: Pathogen pollution and the emergence of a deadly amphibian pathogen.  
39 *Molecular Ecology*, **21(21)**, 5151-5154.
- 40 McKinney, M., 2008: Effects of urbanization on species richness: A review of plants and animals. *Urban*  
41 *Ecosystems*, **11(2)**, 161-176.
- 42 McLachlan, J.S., Clark, J.S., and Manos, P.S., 2005: Molecular indicators of tree migration capacity under rapid  
43 climate change. *Ecology*, **86(8)**, 2088-2098.
- 44 McLaughlin, S.B., Nosal, M., Wullschleger, S.D., and Sun, G., 2007: Interactive effects of ozone and climate on tree  
45 growth and water use in a southern Appalachian forest in the USA. *New Phytologist*, **174(1)**, 109-124.
- 46 McMahan, S.M., Harrison, S.P., Armbruster, W.S., Bartlein, P.J., Beale, C.M., Edwards, M.E., Kattge, J., Midgley,  
47 G., Morin, X., and Prentice, I.C., 2011: Improving assessment and modelling of climate change impacts on  
48 global terrestrial biodiversity. *Trends in Ecology & Evolution*, **26(5)**, 249-259.
- 49 McMenamin, S.K., and Hannah, L., 2012: First Extinctions on Land. In *Saving a Million Species: Extinction Risk*  
50 *from Climate Change* [L. Hannah (ed.)]. Island Press, Washington Covelo London, pp. 89-102.
- 51 McMurtrie, R.E., Iversen, C.M., Dewar, R.C., Medlyn, B.E., Nasholm, T., Pepper, D.A., and Norby, R.J., 2012:  
52 Plant root distributions and nitrogen uptake predicted by a hypothesis of optimal root foraging. *Ecology and*  
53 *Evolution*, **2(6)**, 1235-1250.

- 1 McPherson, R.A., 2007: A review of vegetation-atmosphere interactions and their influences on mesoscale  
2 phenomena. *Progress in Physical Geography*, **31(3)**, 261-285.
- 3 Mehl, J.W., Geldenhuys, C.J., Roux, J., and Wingfield, M.J., 2010: Die-back of kiaat (*Pterocarpus angolensis*) in  
4 southern Africa: a cause for concern? *Southern Forests: a Journal of Forest Science*, **72(3-4)**, 121-132.
- 5 Meier, E.S., Lischke, H., Schmatz, D.R., and Zimmermann, N.E., 2012: Climate, competition and connectivity  
6 affect future migration and ranges of European trees. *Global Ecology and Biogeography*, **21(2)**, 164-178.
- 7 Mendelsohn, R., and Dinar, A., 2009: Land Use and Climate Change Interactions. *Annual Review of Resource  
8 Economics*, **1**, 309-332.
- 9 Menéndez, R., Gonzalez-Megias, A., Lewis, O.T., Shaw, M.R., and Thomas, C.D., 2008: Escape from natural  
10 enemies during climate-driven range expansion: a case study. *Ecological Entomology*, **33(3)**, 413-421.
- 11 Menge, D.N.L., and Field, C.B., 2007: Simulated global changes alter phosphorus demand in annual grassland.  
12 *Global Change Biology*, **13(12)**, 2582-2591.
- 13 Menzel, A., Jakobi, G., Ahas, R., Scheffinger, H., and Estrella, N., 2003: Variations of the climatological growing  
14 season (1951-2000) in Germany compared with other countries. *International Journal of Climatology*, **23(7)**,  
15 793-812.
- 16 Menzel, A., Sparks, T.H., Estrella, N., Koch, E., Aasa, A., Ahas, R., Alm-Kubler, K., Bissolli, P., Braslavská, O.,  
17 Briede, A., Chmielewski, F.M., Crepinsek, Z., Curnel, Y., Dahl, A., Defila, C., Donnelly, A., Filella, Y., Jatcva,  
18 K., Mage, F., Mestre, A., Nordli, O., Penuelas, J., Pirinen, P., Remisova, V., Scheffinger, H., Striz, M., Susnik,  
19 A., Van Vliet, A.J.H., Wielgolaski, F.E., Zach, S., and Züst, A., 2006: European phenological response to  
20 climate change matches the warming pattern. *Global Change Biology*, **12(10)**, 1969-1976.
- 21 Mercado, L.M., Bellouin, N., Sitch, S., Boucher, O., Huntingford, C., Wild, M., and Cox, P.M., 2009: Impact of  
22 changes in diffuse radiation on the global land carbon sink. *Nature*, **458(7241)**, 1014-U1087.
- 23 Merilä, J., 2012: Evolution in response to climate change: In pursuit of the missing evidence. *Bioessays*, **34(9)**, 811-  
24 818.
- 25 Meyers, E.M., Dobrowski, B., and Tague, C.L., 2010: Climate Change Impacts on Flood Frequency, Intensity, and  
26 Timing May Affect Trout Species in Sagehen Creek, California. *Transactions of the American Fisheries  
27 Society*, **139(6)**, 1657-1664.
- 28 Meyfroidt, P., and Lambin, E.F., 2011: Global Forest Transition: Prospects for an End to Deforestation. In *Annual  
29 Review of Environment and Resources*, Vol 36 [A. Gadgil & D. M. Liverman (eds.)]. Annual Reviews, Palo  
30 Alto, pp. 343-371.
- 31 Midgley, G.F., Davies, I.D., Albert, C.H., Altwegg, R., Hannah, L., Hughes, G.O., O'Halloran, L.R., Seo, C.,  
32 Thorne, J.H., and Thuiller, W., 2010: BioMove - an integrated platform simulating the dynamic response of  
33 species to environmental change. *Ecography*, **33(3)**, 612-616.
- 34 Mihoub, J.B., Mouawad, N.G., Pilard, P., Jiguet, F., Low, M., and Teplitsky, C., 2012: Impact of temperature on the  
35 breeding performance and selection patterns in lesser kestrels *Falco naumanni*. *Journal of Avian Biology*, **43(5)**,  
36 472-480.
- 37 Miles, L., Newton, A.C., DeFries, R.S., Ravilious, C., May, I., Blyth, S., Kapos, V., and Gordon, J.E., 2006: A  
38 global overview of the conservation status of tropical dry forests. *Journal of Biogeography*, **33(3)**, 491-505.
- 39 Millar, C., Westfall, R., Delany, D., King, J., and Graumlich, L., 2004: Response of Subalpine Conifers in the Sierra  
40 Nevada, California, U.S.A., to 20th-century Warming and Decadal Climate Variability. *Arctic, Antarctic, and  
41 Alpine Research*, **36(2)**, 181-200.
- 42 Millar, C.I., Westfall, R.D., Delany, D.L., Bokach, M.J., Flint, A.L., and Flint, L.E., 2012: Forest mortality in high-  
43 elevation whitebark pine (*Pinus albicaulis*) forests of eastern California, USA; influence of environmental  
44 context, bark beetles, climatic water deficit, and warming. *Canadian Journal of Forest Research*, **42(4)**, 749-  
45 765.
- 46 Millennium Ecosystem Assessment, 2003: *Ecosystems and Human Wellbeing: A framework for Assessment*. Island  
47 Press, Washington DCpp.
- 48 Millennium Ecosystem Assessment, 2005a: *Ecosystems and Human wellbeing: Biodiversity synthesis*. World  
49 Resources Institute, Washington, DC, 86 pp.
- 50 Millennium Ecosystem Assessment, 2005b: *Ecosystems and human wellbeing: Desertification synthesis*. World  
51 Resources Institute, Washington DCpp.
- 52 Miller-Rushing, A.J., Lloyd-Evans, T.L., Primack, R.B., and Satzing, P., 2008: Bird migration times, climate  
53 change, and changing population sizes. *Global Change Biology*, **14(9)**, 1959-1972.

- 1 Mills, G., Hayes, F., Simpson, D., Emberson, L., Norris, D., Harmens, H., and Buker, P., 2011: Evidence of  
2 widespread effects of ozone on crops and (semi-)natural vegetation in Europe (1990-2006) in relation to  
3 AOT40-and flux-based risk maps. *Global Change Biology*, **17(1)**, 592-613.
- 4 Mills, G., Hayes, F., Wilkinson, S., and Davies, W.J., 2009: Chronic exposure to increasing background ozone  
5 impairs stomatal functioning in grassland species. *Global Change Biology*, **15(6)**, 1522-1533.
- 6 Minter, B.A., and Collins, J.P., 2010: Move it or lose it? The ecological ethics of relocating species under climate  
7 change. *Ecological Applications*, **20(7)**, 1801-1804.
- 8 Miranda, J.D., Padilla, F.M., and Pugnaire, F.I., 2009: Response of a Mediterranean semiarid community to  
9 changing patterns of water supply. *Perspectives in Plant Ecology Evolution and Systematics*, **11(4)**, 255-266.
- 10 Mishra, V., Cherkauer, K.A., Niyogi, D., Lei, M., Pijanowski, B.C., Ray, D.K., Bowling, L.C., and Yang, G., 2010:  
11 A regional scale assessment of land use/land cover and climatic changes on water and energy cycle in the upper  
12 Midwest United States. *International Journal of Climatology*, **30(13)**, 2025-2044.
- 13 Mitas, C.M., and Clement, A., 2005: Has the Hadley cell been strengthening in recent decades? *Geophysical  
14 Research Letters*, **32(3)**.
- 15 Mitchard, E.T.A., Saatchi, S.S., Gerard, F.F., Lewis, S.L., and Meir, P., 2009: Measuring woody encroachment  
16 along a forest-savanna boundary in Central Africa. *Earth Interactions*, **13(8)**, 1-29.
- 17 Mitchell, T.D., and Jones, P.D., 2005: An improved method of constructing a database of monthly climate  
18 observations and associated high-resolution grids. *International Journal of Climatology*, **25(6)**, 693-712.
- 19 Miyake, S., Renouf, M., Peterson, A., McAlpine, C., and Smith, C., 2012: Land-use and environmental pressures  
20 resulting from current and future bioenergy crop expansion: A review. *Journal of Rural Studies*, **28(4)**, 650-658.
- 21 Moiseyev, A., Solberg, B., Kallio, A.M.I., and Lindner, M., 2011: An economic analysis of the potential  
22 contribution of forest biomass to the EU RES target and its implications for the EU forest industries. *Journal of  
23 Forest Economics*, **17(2)**, 197-213.
- 24 Moleele, N.M., Ringrose, S., Matheson, W., and Vanderpost, C., 2002: More woody plants? The status of bush  
25 encroachment in Botswana's grazing areas. *Journal of Environmental Management*, **64(1)**, 3-11.
- 26 Møller, A.P., Rubolini, D., and Lehikoinen, E., 2008: Populations of migratory bird species that did not show a  
27 phenological response to climate change are declining. *Proceedings of the National Academy of Sciences of the  
28 United States of America*, **105(42)**, 16195-16200.
- 29 Monahan, W.B., and Tingley, M.W., 2012: Niche Tracking and Rapid Establishment of Distributional Equilibrium  
30 in the House Sparrow Show Potential Responsiveness of Species to Climate Change. *PLoS One*, **7(7)**.
- 31 Monteith, J.L., 1965: Evaporation and environment. *Symp. Soc. Exp. Biol.*, **19**, 205-224.
- 32 Montoya, J.M., and Raffaelli, D., 2010: The effects of climate change on biotic interactions and ecosystem services.  
33 *Philosophical Transactions of the Royal Society B-Biological Sciences*, **365(1549)**, 2011-2011.
- 34 Mooney, H.A., Bullock, S.H., and Medina, E., 1995: Introduction. In *Seasonally dry tropical forests* [S. H. Bullock,  
35 H. A. Mooney & E. Medina (eds.)]. Cambridge University Press, Cambridge, UK, pp. 1-8.
- 36 Morecroft, M.D., Crick, H.Q.P., Duffield, S.J., and Macgregor, N.A., 2012: Resilience to climate change: translating  
37 principles into practice. *Journal of Applied Ecology*, **49(3)**, 547-551.
- 38 Morin, X., Augspurger, C., and Chuine, I., 2007: Process-based modeling of species' distributions: What limits  
39 temperate tree species' range boundaries? *Ecology*, **88(9)**, 2280-2291.
- 40 Morin, X., and Thuiller, W., 2009: Comparing niche- and process-based models to reduce prediction uncertainty in  
41 species range shifts under climate change. *Ecology*, **90(5)**, 1301-1313.
- 42 Moritz, M.A., Parisien, M.A., Batllori, E., Krawchuk, M.A., Van Dorn, J., Ganz, D.J., and Hayhoe, K., 2012:  
43 Climate change and disruptions to global fire activity. *Ecosphere*, **3(49)**.
- 44 Morrison, J., Quick, M.C., and Foreman, M.G.G., 2002: Climate change in the Fraser River watershed: flow and  
45 temperature projections. *Journal of Hydrology*, **263(1-4)**, 230-244.
- 46 Mueller, A.D., Islebe, G.A., Hillesheim, M.B., Grzesik, D.A., Anselmetti, F.S., Ariztegui, D., Brenner, M., Curtis,  
47 J.H., Hodell, D.A., and Venz, K.A., 2009a: Climate drying and associated forest decline in the lowlands of  
48 northern Guatemala during the late Holocene. *Quaternary Research*, **71(2)**, 133-141.
- 49 Mueller, D.R., Van Hove, P., Antoniadis, D., Jeffries, M.O., and Vincent, W.F., 2009b: High Arctic lakes as  
50 sentinel ecosystems: Cascading regime shifts in climate, ice cover, and mixing. *Limnology and Oceanography*,  
51 **54(6)**, 2371-2385.
- 52 Mueller, R.C., Scudder, C.M., Porter, M.E., Trotter, R.T., Gehring, C.A., and Whitham, T.G., 2005: Differential tree  
53 mortality in response to severe drought: evidence for long-term vegetation shifts. *Journal of Ecology*, **93(6)**,  
54 1085-1093.

- 1 Muhlfeld, C.C., Giersch, J.J., Hauer, F.R., Pederson, G.T., Luikart, G., Peterson, D.P., Downs, C.C., and Fagre,  
2 D.B., 2011: Climate change links fate of glaciers and an endemic alpine invertebrate. *Climatic Change*, **106(2)**,  
3 337-345.
- 4 Murdiyarsa, D., Hergoualc'h, K., and Verchot, L.V., 2010: Opportunities for reducing greenhouse gas emissions in  
5 tropical peatlands. *Proceedings of the National Academy of Sciences of the United States of America*, **107(46)**,  
6 19655-19660.
- 7 Musolin, D.L., Tougou, D., and Fujisaki, K., 2010: Too hot to handle? Phenological and life-history responses to  
8 simulated climate change of the southern green stink bug *Nezara viridula* (Heteroptera: Pentatomidae). *Global*  
9 *Change Biology*, **16(1)**, 73-87.
- 10 Myers-Smith, I.H., Forbes, B.C., Wilmking, M., Hallinger, M., Lantz, T., Blok, D., Tape, K.D., Macias-Fauria, M.,  
11 Sass-Klaassen, U., Levesque, E., Boudreau, S., Ropars, P., Hermanutz, L., Trant, A., Collier, L.S., Weijers, S.,  
12 Rozema, J., Rayback, S.A., Schmidt, N.M., Schaepman-Strub, G., Wipf, S., Rixen, C., Menard, C.B., Venn, S.,  
13 Goetz, S., Andreu-Hayles, L., Elmendorf, S., Ravolainen, V., Welker, J., Grogan, P., Epstein, H.E., and Hik,  
14 D.S., 2011: Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities. *Environmental*  
15 *Research Letters*, **6(4)**, 1-15.
- 16 Nabuurs, G.J., Hengeveld, G.M., van der Werf, D.C., and Heidema, A.H., 2010: European forest carbon balance  
17 assessed with inventory based methods—An introduction to a special section. *Forest Ecology and Management*,  
18 **260(3)**, 239-240.
- 19 Naef-Daenzer, B., Luterbacher, J., Nuber, M., Rutishauser, T., and Winkel, W., 2012: Cascading climate effects and  
20 related ecological consequences during past centuries. *Climate of the Past*, **8(5)**, 1527-1540.
- 21 Naito, A.T., and Cairns, D.M., 2011: Patterns and processes of global shrub expansion. *Progress in Physical*  
22 *Geography*, **35(4)**, 423-442.
- 23 Nakazawa, T., and Doi, H., 2012: A perspective on match/mismatch of phenology in community contexts. *Oikos*,  
24 **121(4)**, 489-495.
- 25 Nathan, R., 2006: Long-distance dispersal of plants. *Science*, **313(5788)**, 786-788.
- 26 Nathan, R., Horvitz, N., He, Y.P., Kuparinen, A., Schurr, F.M., and Katul, G.G., 2011: Spread of North American  
27 wind-dispersed trees in future environments. *Ecology Letters*, **14(3)**, 211-219.
- 28 Nemet, G.F., 2009: Net Radiative Forcing from Widespread Deployment of Photovoltaics. *Environmental Science*  
29 *and Technology*, **43(6)**, 2173-2178.
- 30 Nepstad, D.C., Boyd, W., Stickler, C.M., Azevedo, A., and Bezerra, T., in press: Responding to Climate Change and  
31 the Global Land Crisis: REDD+, Market Transformation, and Low Emissions Rural Development.  
32 *Philosophical Transactions of the Royal Society - B*.
- 33 Nepstad, D.C., Stickler, C.M., Soares, B., and Merry, F., 2008: Interactions among Amazon land use, forests and  
34 climate: prospects for a near-term forest tipping point. *Philosophical Transactions of the Royal Society B-*  
35 *Biological Sciences*, **363(1498)**, 1737-1746.
- 36 Nepstad, D.C., Tohver, I.M., Ray, D., Moutinho, P., and Cardinot, G., 2007: Mortality of large trees and lianas  
37 following experimental drought in an amazon forest. *Ecology*, **88(9)**, 2259-2269.
- 38 Ni, J., 2011: Impacts of climate change on Chinese ecosystems: key vulnerable regions and potential thresholds.  
39 *Regional Environmental Change*, **11**, S49-S64.
- 40 Niboyet, A., Brown, J.R., Dijkstra, P., Blankinship, J.C., Leadley, P.W., Le Roux, X., Barthes, L., Barnard, R.L.,  
41 Field, C.B., and Hungate, B.A., 2011: Global Change Could Amplify Fire Effects on Soil Greenhouse Gas  
42 Emissions. *PLoS One*, **6(6)**, 1-10.
- 43 Nicholls, R.J., 2004: Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and  
44 socio-economic scenarios. *Global Environmental Change-Human and Policy Dimensions*, **14(1)**, 69-86.
- 45 Nilsson, C., Reidy, C.A., Dynesius, M., and Revenga, C., 2005: Fragmentation and flow regulation of the world's  
46 large river systems. *Science*, **308(5720)**, 405-408.
- 47 Noble, I.R., Gill, A.M., and Bary, G.A.V., 1980: McArthur's fire-danger meters expressed as equations. *Australian*  
48 *Journal of Ecology*, **5(2)**, 201-203.
- 49 Nock, C.A., Baker, P.J., Wanek, W., Leis, A., Grabner, M., Bunyavejchewin, S., and Hietz, P., 2011: Long-term  
50 increases in intrinsic water-use efficiency do not lead to increased stem growth in a tropical monsoon forest in  
51 western Thailand. *Global Change Biology*, **17(2)**, 1049-1063.
- 52 Nogues-Bravo, D., Ohlemuller, R., Batra, P., and Araujo, M.B., 2010: Climate Predictors of Late Quaternary  
53 Extinctions. *Evolution*, **64(8)**, 2442-2449.

- 1 Norberg, J., Urban, M.C., Vellend, M., Klausmeier, C.A., and Loeuille, N., 2012: Eco-evolutionary responses of  
2 biodiversity to climate change. *Nature Climate Change*, **2(10)**, 747-751.
- 3 Norby, R.J., Warren, J.M., Iversen, C.M., Medlyn, B.E., and McMurtrie, R.E., 2010: CO<sub>2</sub> enhancement of forest  
4 productivity constrained by limited nitrogen availability. *Proceedings of the National Academy of Sciences*,  
5 **107(45)**, 19368-19373.
- 6 Norby, R.J., and Zak, D.R., 2011: Ecological Lessons from Free-Air CO<sub>2</sub> Enrichment (FACE) Experiments. In  
7 *Annual Review of Ecology, Evolution, and Systematics, Vol 42* [D. J. Futuyma, H. B. Shaffer & D. Simberloff  
8 (eds.)]. Annual Reviews, Palo Alto, pp. 181-203.
- 9 Normand, S., Treier, U.A., Randin, C., Vittoz, P., Guisan, A., and Svenning, J.C., 2009: Importance of abiotic stress  
10 as a range-limit determinant for European plants: insights from species responses to climatic gradients. *Global  
11 Ecology and Biogeography*, **18(4)**, 437-449.
- 12 Nowicki, P., Pepkowska, A., Kudlek, J., Skorka, P., Witek, M., Settele, J., and Woyciechowski, M., 2007: From  
13 metapopulation theory to conservation recommendations: Lessons from spatial occurrence and abundance  
14 patterns of *Maculinea* butterflies. *Biological Conservation*, **140(1-2)**, 119-129.
- 15 O'Connor, F.M., Boucher, O., Gedney, N., Jones, C.D., Folberth, G.A., Coppel, R., Friedlingstein, P., Collins, W.J.,  
16 Chappellaz, J., Ridley, J., and Johnson, C.E., 2010: Possible role of wetlands, permafrost, and methane hydrates  
17 in the methane cycle under future climate change: a review. *Reviews of Geophysics*, **48(RG4005)**, 1-33.
- 18 O'Donnell, J.A., Harden, J.W., McGuire, A.D., Kanevskiy, M.Z., Jorgenson, M.T., and Xu, X.M., 2011: The effect  
19 of fire and permafrost interactions on soil carbon accumulation in an upland black spruce ecosystem of interior  
20 Alaska: implications for post-thaw carbon loss. *Global Change Biology*, **17(3)**, 1461-1474.
- 21 O'Halloran, T.L., Law, B.E., Goulden, M.L., Wang, Z., Barr, J.G., Schaaf, C., Brown, M., Fuentes, J.D., Göckede,  
22 M., Black, A., and Engel, V., 2012: Radiative forcing of natural forest disturbances. *Global Change Biology*,  
23 **18(2)**, 555-565.
- 24 O'Reilly, C.M., Alin, S.R., Plisnier, P.D., Cohen, A.S., and McKee, B.A., 2003: Climate change decreases aquatic  
25 ecosystem productivity of Lake Tanganyika, Africa. *Nature*, **424(6950)**, 766-768.
- 26 OECD/FAO, 2010: *OECD-FAO Agricultural Outlook 2010-2019*. 248 pp.
- 27 Ogawa-Onishi, Y., Berry, P.M., and Tanaka, N., 2010: Assessing the potential impacts of climate change and their  
28 conservation implications in Japan: A case study of conifers. *Biological Conservation*, **143(7)**, 1728-1736.
- 29 Oleszczuk, R., Regina, K., Szajdak, L., Höper, H., and Maryganova, V., 2008: Impacts of agricultural utilization of  
30 peat soils on the greenhouse gas balance. In *Peatlands and climate change* [M. Strack (ed.)]. International Peat  
31 Society, Finland, pp. 70-97.
- 32 Oliver, T., Hill, J.K., Thomas, C.D., Brereton, T., and Roy, D.B., 2009: Changes in habitat specificity of species at  
33 their climatic range boundaries. *Ecology Letters*, **12(10)**, 1091-1102.
- 34 Oliver, T.H., Gillings, S., Girardello, M., Rapacciuolo, G., Brereton, T.M., Siriwardena, G.M., Roy, D.B., Pywell,  
35 R., and Fuller, R.J., 2012: Population density but not stability can be predicted from species distribution models.  
36 *Journal of Applied Ecology*, **49(3)**, 581-590.
- 37 Oltmans, S.J., Lefohn, A.S., Harris, J.M., Tarasick, D.W., Thompson, A.M., Wernli, H., Johnson, B.J., Novelli,  
38 P.C., Montzka, S.A., Ray, J.D., Patrick, L.C., Sweeney, C., Jefferson, A., Dann, T., and Davies, J., 2006: Long  
39 term changes in tropospheric ozone. *Atmospheric Environment*, **40(17)**, 3156-3173.
- 40 Ormerod, S.J., 2009: Climate change, river conservation and the adaptation challenge. *Aquatic Conservation:  
41 Marine and Freshwater Ecosystems*, **19(6)**, 609-613.
- 42 Osawa, A., Zyryanova, O.A., Matsuura, Y., Kajimoto, T., and Wein, R.W., 2010: *Permafrost Ecosystems: Siberian  
43 Larch Forests*. Springer, New York, 502 pp.
- 44 Ozgul, A., Childs, D.Z., Oli, M.K., Armitage, K.B., Blumstein, D.T., Olson, L.E., Tuljapurkar, S., and Coulson, T.,  
45 2010: Coupled dynamics of body mass and population growth in response to environmental change. *Nature*,  
46 **466(7305)**, 482-U485.
- 47 Paerl, H.W., Hall, N.S., and Calandrino, E.S., 2011: Controlling harmful cyanobacterial blooms in a world  
48 experiencing anthropogenic and climatic-induced change. *Science of the Total Environment*, **409(10)**, 1739-  
49 1745.
- 50 Paerl, H.W., and Paul, V.J., 2012: Climate change: links to global expansion of harmful cyanobacteria. *Water Res*,  
51 **46(5)**, 1349-1363.
- 52 Page, S.E., Rieley, J.O., and Banks, C.J., 2011: Global and regional importance of the tropical peatland carbon pool.  
53 *Global Change Biology*, **17(2)**, 798-818.



- 1 Page, S.E., Siegert, F., Rieley, J.O., Boehm, H.D., Jaya, A., and Limin, S., 2002: The amount of carbon released  
2 from peat and forest fires in Indonesia during 1997. *Nature*, **420(6911)**, 61-65.
- 3 Palmer, M.A., and Filoso, S., 2009: Restoration of Ecosystem Services for Environmental Markets. *Science*,  
4 **325(5940)**, 575-576.
- 5 Pan, Y., Birdsey, R., Fang, J., Houghton, R., Kauppi, P., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L.,  
6 Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., and  
7 Hayes, D., 2011: A Large and Persistent Carbon Sink in the World's Forests. *Science*, **333(6045)**, 988-993.
- 8 Pan, Y.D., Birdsey, R., Hom, J., and McCullough, K., 2009: Separating effects of changes in atmospheric  
9 composition, climate and land-use on carbon sequestration of US Mid-Atlantic temperate forests. *Forest*  
10 *Ecology and Management*, **259(2)**, 151-164.
- 11 Parent, M.B., and Verbyla, D., 2010: The Browning of Alaska's Boreal Forest. *Remote Sensing*, **2(12)**, 2729-2747.
- 12 Park Williams, A., Allen, C.D., Macalady, A.K., Griffin, D., Woodhouse, C.A., Meko, D.M., Swetnam, T.W.,  
13 Rauscher, S.A., Seager, R., Grissino-Mayer, H.D., Dean, J.S., Cook, E.R., Gangodagamage, C., Cai, M., and  
14 McDowell, N.G., 2012: Temperature as a potent driver of regional forest drought stress and tree mortality.  
15 *Nature Climate Change*, **advance online publication**.
- 16 Parker-Allie, F., Musil, C.F., and Thuiller, W., 2009: Effects of climate warming on the distributions of invasive  
17 Eurasian annual grasses: a South African perspective. *Climatic Change*, **94(1-2)**, 87-103.
- 18 Parker, B.R., Vinebrooke, R.D., and Schindler, D.W., 2008: Recent climate extremes alter alpine lake ecosystems.  
19 *Proceedings of the National Academy of Sciences of the United States of America*, **105(35)**, 12927-12931.
- 20 Parmesan, C., 2006: Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology*  
21 *Evolution and Systematics*, **37**, 637-669.
- 22 Parmesan, C., 2007: Influences of species, latitudes and methodologies on estimates of phenological response to  
23 global warming. *Global Change Biology*, **13(9)**, 1860-1872.
- 24 Parmesan, C., and Yohe, G., 2003: A globally coherent fingerprint of climate change impacts across natural systems.  
25 *Nature*, **421(6918)**, 37-42.
- 26 Pateman, R.M., Hill, J.K., Roy, D.B., Fox, R., and Thomas, C.D., 2012: Temperature-Dependent Alterations in Host  
27 Use Drive Rapid Range Expansion in a Butterfly. *Science*, **336(6084)**, 1028-1030.
- 28 Pauli, H., Gottfried, M., Dullinger, S., Abdaladze, O., Akhalkatsi, M., Alonso, J.L.B., Coldea, G., Dick, J.,  
29 Erschbamer, B., Calzado, R.F., Ghosn, D., Holten, J.I., Kanka, R., Kazakis, G., Kollar, J., Larsson, P., Moiseev,  
30 P., Moiseev, D., Molau, U., Mesa, J.M., Nagy, L., Pelino, G., Puscas, M., Rossi, G., Stanisci, A., Syverhuset,  
31 A.O., Theurillat, J.P., Tomaselli, M., Unterluggauer, P., Villar, L., Vittoz, P., and Grabherr, G., 2012: Recent  
32 Plant Diversity Changes on Europe's Mountain Summits. *Science*, **336(6079)**, 353-355.
- 33 Pauli, H., Gottfried, M., Reiter, K., Klettner, C., and Grabherr, G., 2007: Signals of range expansions and  
34 contractions of vascular plants in the high Alps: observations (1994-2004) at the GLORIA master site  
35 Schrankogel, Tyrol, Austria. *Global Change Biology*, **13**, 147-156.
- 36 Pauls, S.U., Nowak, C., Bálint, M., and Pfenninger, M., 2013: The impact of global climate change on genetic  
37 diversity within populations and species. *Molecular Ecology*, **22(4)**, 925-946.
- 38 Paun, O., Bateman, R.M., Fay, M.F., Hedren, M., Civeyrel, L., and Chase, M.W., 2010: Stable Epigenetic Effects  
39 Impact Adaptation in Allopolyploid Orchids (*Dactylorhiza*: Orchidaceae). *Molecular Biology and Evolution*,  
40 **27(11)**, 2465-2473.
- 41 Payette, S., 2007: Contrasted dynamics of northern Labrador tree lines caused by climate change and migrational  
42 lag. *Ecology*, **88(3)**, 770-780.
- 43 Payette, S., and Fillion, L., 1985: White spruce expansion at the tree line and recent climatic change. *Canadian*  
44 *Journal of Forest Research*, **15(1)**, 241-251.
- 45 Pearce-Higgins, J.W., Stephen, L., Douse, A., and Langston, R.H.W., 2012: Greater impacts of wind farms on bird  
46 populations during construction than subsequent operation: results of a multi-site and multi-species analysis.  
47 *Journal of Applied Ecology*, **49(2)**, 386-394.
- 48 Pearlstine, L.G., Pearlstine, E.V., and Aumen, N.G., 2010: A review of the ecological consequences and  
49 management implications of climate change for the Everglades. *Journal of the North American Benthological*  
50 *Society*, **29(4)**, 1510-1526.
- 51 Pearman, P.B., Randin, C.F., Broennimann, O., Vittoz, P., van der Knaap, W.O., Engler, R., Le Lay, G.,  
52 Zimmermann, N.E., and Guisan, A., 2008: Prediction of plant species distributions across six millennia.  
53 *Ecology Letters*, **11(4)**, 357-369.

- 1 Pearson, R.G., 2006: Climate change and the migration capacity of species. *Trends in Ecology & Evolution*, **21(3)**,  
2 111-113.
- 3 Pearson, R.G., 2011: *Driven to Extinction: The Impact of Climate Change on Biodiversity*. American Museum of  
4 Natural History, Washingtonpp.
- 5 Pearson, R.G., and Dawson, T.P., 2003: Predicting the impacts of climate change on the distribution of species: are  
6 bioclimate envelope models useful? *Global Ecology and Biogeography*, **12(5)**, 361-371.
- 7 Pearson, R.G., Phillips, S.J., Loranty, M.M., Beck, P.S.A., Damoulas, T., Knight, S.J., and Goetz, S.J., 2013: Arctic  
8 vegetation distribution shifts and associated feedbacks under future climate change. *Nature Climate Change*, in  
9 press.
- 10 Pederson, G.T., Graumlich, L.J., Fagre, D.B., Kipfer, T., and Muhlfeld, C.C., 2010: A century of climate and  
11 ecosystem change in Western Montana: what do temperature trends portend? *Climatic Change*, **98(1-2)**, 133-  
12 154.
- 13 Peltzer, D.A., Allen, R.B., Lovett, G.M., Whitehead, D., and Wardle, D.A., 2010: Effects of biological invasions on  
14 forest carbon sequestration. *Global Change Biology*, **16(2)**, 732-746.
- 15 Peng, C., Ma, Z., Lei, X., Zhu, Q., Chen, H., Wang, W., Liu, S., Li, W., Fang, X., and Zhou, X., 2011: A drought-  
16 induced pervasive increase in tree mortality across Canada's boreal forests. *Nature Clim. Change*, **1(9)**, 467-  
17 471.
- 18 Peng, C., Zhou, X., Zhao, S., Wang, X., Zhu, B., Piao, S., and Fang, J., 2009: Quantifying the response of forest  
19 carbon balance to future climate change in Northeastern China: model validation and prediction. *Global and  
20 Planetary Change*, **66(3-4)**, 179-194.
- 21 Penman, H.L., 1948: Natural evaporation from open water, bare soil and grass *Proceedings of the Royal Society of  
22 London. Series A: Mathematical and Physical Sciences*, **93**, 120-145.
- 23 Peñuelas, J., and Boada, M., 2003: A global change-induced biome shift in the Montseny mountains (NE Spain).  
24 *Global Change Biology*, **9(2)**, 131-140.
- 25 Peñuelas, J., Canadell, J.G., and Ogaya, R., 2011: Increased water-use efficiency during the 20th century did not  
26 translate into enhanced tree growth. *Global Ecology and Biogeography*, **20(4)**, 597-608.
- 27 Peñuelas, J., Gordon, C., Llorens, L., Nielsen, T., Tietema, A., Beier, C., Bruna, P., Emmett, B., Estiarte, M., and  
28 Gorissen, A., 2004: Noninvasive field experiments show different plant responses to warming and drought  
29 among sites, seasons, and species in a north-south European gradient. *Ecosystems*, **7(6)**, 598-612.
- 30 Peñuelas, J., Prieto, P., Beier, C., Cesaraccio, C., de Angelis, P., de Dato, G., Emmett, B.A., Estiarte, M., Garadnai,  
31 J., Gorissen, A., Lang, E.K., Kroel-Dulay, G., Llorens, L., Pellizzaro, G., Riis-Nielsen, T., Schmidt, I.K., Sirca,  
32 C., Sowerby, A., Spano, D., and Tietema, A., 2007: Response of plant species richness and primary productivity  
33 in shrublands along a north-south gradient in Europe to seven years of experimental warming and drought:  
34 reductions in primary productivity in the heat and drought year of 2003. *Global Change Biology*, **13(12)**, 2563-  
35 2581.
- 36 Peñuelas, J., Sardans, J., Rivas-Ubach, A., and Janssens, I.A., 2012: The human-induced imbalance between C, N  
37 and P in Earth's life system. *Global Change Biology*, **18(1)**, 3-6.
- 38 Pereira, H.M., Leadley, P.W., Proenca, V., Alkemade, R., Scharlemann, J.P.W., Fernandez-Manjarres, J.F., Araujo,  
39 M.B., Balvanera, P., Biggs, R., Cheung, W.W.L., Chini, L., Cooper, H.D., Gilman, E.L., Guenette, S., Hurtt,  
40 G.C., Huntington, H.P., Mace, G.M., Oberdorff, T., Revenga, C., Rodrigues, P., Scholes, R.J., Sumaila, U.R.,  
41 and Walpole, M., 2010: Scenarios for Global Biodiversity in the 21st Century. *Science*, **330(6010)**, 1496-1501.
- 42 Perry, L.G., Andersen, D.C., Reynolds, L.V., Nelson, S.M., and Shafroth, P.B., 2012: Vulnerability of riparian  
43 ecosystems to elevated CO<sub>2</sub> and climate change in arid and semiarid western North America. *Global Change  
44 Biology*, **18(3)**, 821-842.
- 45 Peterken, G.F., and Mountford, E.P., 1996: Effects of drought on beech in Lady Park Wood, an unmanaged mixed  
46 deciduous woodland. *Forestry*, **69(2)**, 125-136.
- 47 Peterson, A.T., Stewart, A., Mohamed, K.I., and Araujo, M.B., 2008: Shifting Global Invasive Potential of European  
48 Plants with Climate Change. *PLoS One*, **3(6)**, 1-7.
- 49 Peterson, A.T.S., J., Pearson, R.G., Anderson, R.P., Martínez-Meyer, E., Nakamura, M., and Araújo, M.B., 2011:  
50 *Ecological Niches and Geographic Distributions*. Princeton University Press, Princeton, NJ, USA, 328 pp.
- 51 Petit, B., and Montagnini, F., 2006: Growth in pure and mixed plantations of tree species used in reforesting rural  
52 areas of the humid region of Costa Rica, Central America. *Forest Ecology and Management*, **233(2-3)**, 338-  
53 343.

- 1 Petitpierre, B., Kueffer, C., Broennimann, O., Randin, C., Daehler, C., and Guisan, A., 2012: Climatic Niche Shifts  
2 Are Rare Among Terrestrial Plant Invaders. *Science*, **335(6074)**, 1344-1348.
- 3 Peylin, P., Bousquet, P., Le Quere, C., Friedlingstein, P., McKinley, G., Gruber, N., Rayner, P., and Ciais, P., 2005:  
4 Multiple constraints on regional CO<sub>2</sub> flux variations over land and oceans. *Global Biogeochemical Cycles*,  
5 **19(1)**, 1-21.
- 6 Phillimore, A.B., Hadfield, J.D., Jones, O.R., and Smithers, R.J., 2010: Differences in spawning date between  
7 populations of common frog reveal local adaptation. *Proceedings of the National Academy of Sciences of the*  
8 *United States of America*, **107(18)**, 8292-8297.
- 9 Phillips, O.L., Aragao, L., Lewis, S.L., Fisher, J.B., Lloyd, J., Lopez-Gonzalez, G., Malhi, Y., Monteagudo, A.,  
10 Peacock, J., Quesada, C.A., van der Heijden, G., Almeida, S., Amaral, I., Arroyo, L., Aymard, G., Baker, T.R.,  
11 Banki, O., Blanc, L., Bonal, D., Brando, P., Chave, J., de Oliveira, A.C.A., Cardozo, N.D., Czimczik, C.I.,  
12 Feldpausch, T.R., Freitas, M.A., Gloor, E., Higuchi, N., Jimenez, E., Lloyd, G., Meir, P., Mendoza, C., Morel,  
13 A., Neill, D.A., Nepstad, D., Patino, S., Penuela, M.C., Prieto, A., Ramirez, F., Schwarz, M., Silva, J., Silveira,  
14 M., Thomas, A.S., ter Steege, H., Stropp, J., Vasquez, R., Zelazowski, P., Davila, E.A., Andelman, S., Andrade,  
15 A., Chao, K.J., Erwin, T., Di Fiore, A., Honorio, E., Keeling, H., Killeen, T.J., Laurance, W.F., Cruz, A.P.,  
16 Pitman, N.C.A., Vargas, P.N., Ramirez-Angulo, H., Rudas, A., Salamao, R., Silva, N., Terborgh, J., and Torres-  
17 Lezama, A., 2009: Drought Sensitivity of the Amazon Rainforest. *Science*, **323(5919)**, 1344-1347.
- 18 Phillips, O.L., Martinez, R.V., Arroyo, L., Baker, T.R., Killeen, T., Lewis, S.L., Malhi, Y., Mendoza, A.M., Neill,  
19 D., Vargas, P.N., Alexiades, M., Ceron, C., Di Fiore, A., Erwin, T., Jardim, A., Palacios, W., Saldias, M., and  
20 Vinceti, B., 2002: Increasing dominance of large lianas in Amazonian forests. *Nature*, **418(6899)**, 770-774.
- 21 Phillips, O.L., van der Heijden, G., Lewis, S.L., Lopez-Gonzalez, G., Aragao, L.E.O.C., Lloyd, J., Malhi, Y.,  
22 Monteagudo, A., Almeida, S., Alvarez Davila, E., Amaral, I., Andelman, S., Andrade, A., Arroyo, L., Aymard,  
23 G., Baker, T.R., Blanc, L., Bonal, D., Alves de Oliveira, A.C., Chao, K.-J., Davila Cardozo, N., da Costa, L.,  
24 Feldpausch, T.R., Fisher, J.B., Fyllas, N.M., Freitas, M.A., Galbraith, D., Gloor, E., Higuchi, N., Honorio, E.,  
25 Jimenez, E., Keeling, H., Killeen, T.J., Lovett, J.C., Meir, P., Mendoza, C., Morel, A., Nunez Vargas, P., Patino,  
26 S., Peh, K.S.H., Pena Cruz, A., Prieto, A., Quesada, C.A., Ramirez, F., Ramirez, H., Rudas, A., Salamao, R.,  
27 Schwarz, M., Silva, J., Silveira, M., Slik, J.W.F., Sonke, B., Thomas, A.S., Stropp, J., Taplin, J.R.D., Vasquez,  
28 R., and Vilanova, E., 2010: Drought-mortality relationships for tropical forests. *New Phytologist*, **187(3)**, 631-  
29 646.
- 30 Phillips, O.L., Vásquez Martínez, R., Monteagudo Mendoza, A., Baker, T., and Núñez-Vargas, P., 2005: Large  
31 lianas as hyperdynamic elements of the tropical forest canopy. *Ecology*, **86(5)**, 1250-1258.
- 32 Pielke, R.A., Pitman, A., Niyogi, D., Mahmood, R., McAlpine, C., Hossain, F., Goldewijk, K.K., Nair, U., Betts, R.,  
33 Fall, S., Reichstein, M., Kabat, P., and de Noblet, N., 2011: Land use/land cover changes and climate: modeling  
34 analysis and observational evidence. *Wiley Interdisciplinary Reviews-Climate Change*, **2(6)**, 828-850.
- 35 Pitman, A.J., de Noblet-Ducoudre, N., Cruz, F.T., Davin, E.L., Bonan, G.B., Brovkin, V., Claussen, M., Delire, C.,  
36 Ganzeveld, L., Gayler, V., van den Hurk, B.J.J.M., Lawrence, P.J., van der Molen, M.K., Muller, C., Reick,  
37 C.H., Seneviratne, S.I., Strengers, B.J., and Voldoire, A., 2009: Uncertainties in climate responses to past land  
38 cover change: First results from the LUCID intercomparison study. *Geophysical Research Letters*, **36(L08702)**,  
39 1-6.
- 40 Pitman, A.J., Narisma, G.T., and McAneney, J., 2007: The impact of climate change on the risk of forest and  
41 grassland fires in Australia. *Climatic Change*, **84(3-4)**, 383-401.
- 42 Ponniah, M., and Hughes, J.M., 2004: The evolution of Queensland spiny mountain crayfish of the genus *Euastacus*.  
43 I. Testing vicariance and dispersal with interspecific mitochondrial DNA. *Evolution*, **58(5)**, 1073-1085.
- 44 Porter, T.J., and Pisaric, M.F.J., 2011: Temperature-growth divergence in white spruce forests of Old Crow Flats,  
45 Yukon Territory, and adjacent regions of northwestern North America. *Global Change Biology*, **17(11)**, 3418-  
46 3430.
- 47 Post, E., Forchhammer, M.C., Bret-Harte, M.S., Callaghan, T.V., Christensen, T.R., Elberling, B., Fox, A.D., Gilg,  
48 O., Hik, D.S., Hoye, T.T., Ims, R.A., Jeppesen, E., Klein, D.R., Madsen, J., McGuire, A.D., Rysgaard, S.,  
49 Schindler, D.E., Stirling, I., Tamstorf, M.P., Tyler, N.J.C., van der Wal, R., Welker, J., Wookey, P.A., Schmidt,  
50 N.M., and Aastrup, P., 2009: Ecological Dynamics Across the Arctic Associated with Recent Climate Change.  
51 *Science*, **325(5946)**, 1355-1358.
- 52 Post, E., Pedersen, C., Wilmers, C.C., and Forchhammer, M.C., 2008: Warming, plant phenology and the spatial  
53 dimension of trophic mismatch for large herbivores. *Proceedings of the Royal Society B: Biological Sciences*,  
54 **275(1646)**, 2005-2013.

- 1 Potts, S.G., Biesmeijer, J.C., Kremen, C., Neumann, P., Schweiger, O., and Kunin, W.E., 2010: Global pollinator  
2 declines: trends, impacts and drivers. *Trends in Ecology & Evolution*, **25(6)**, 345-353.
- 3 Potvin, C., Chapin, F., Gonzalez, A., Leadley, P., Reich, P., and Roy, J., 2007: Plant Biodiversity and Responses to  
4 Elevated Carbon Dioxide. In *Terrestrial Ecosystems in a Changing World*. *Global Change* [J. G. Canadell, D.  
5 E. Pataki & L. F. Pitelka (eds.)]. Springer, Berlin, pp. 103-112.
- 6 Pounds, J.A., Bustamante, M.R., Coloma, L.A., Consuegra, J.A., Fogden, M.P.L., Foster, P.N., La Marca, E.,  
7 Masters, K.L., Merino-Viteri, A., Puschendorf, R., Ron, S.R., Sanchez-Azofeifa, G.A., Still, C.J., and Young,  
8 B.E., 2006: Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature*,  
9 **439(7073)**, 161-167.
- 10 Prentice, I.C., Guiot, J., Huntley, B., Jolly, D., and Cheddadi, R., 1996: Reconstructing biomes from  
11 palaeoecological data: a general method and its application to European pollen data at 0 and 6 ka. *Climate*  
12 *Dynamics*, **12**, 185-194.
- 13 Prentice, I.C., and Harrison, S.P., 2009: Ecosystem effects of CO(2) concentration: evidence from past climates.  
14 *Climate of the Past*, **5(3)**, 297-307.
- 15 Prentice, I.C., Harrison, S.P., and Bartlein, P.J., 2011: Global vegetation and terrestrial carbon cycle changes after  
16 the last ice age. *New Phytologist*, **189(4)**, 988-998.
- 17 Prieto, P., Penuelas, J., Llusia, J., Asensio, D., and Estiarte, M., 2009: Effects of long-term experimental night-time  
18 warming and drought on photosynthesis, Fv/Fm and stomatal conductance in the dominant species of a  
19 Mediterranean shrubland. *Acta Physiologiae Plantarum*, **31(4)**, 729-739.
- 20 Primack, R.B., Ibáñez, I., Higuchi, H., Lee, S.D., Miller-Rushing, A.J., Wilson, A.M., and Silander Jr, J.A., 2009:  
21 Spatial and interspecific variability in phenological responses to warming temperatures. *Biological*  
22 *Conservation*, **142(11)**, 2569-2577.
- 23 Prince, S.D., Wessels, K.J., Tucker, C.J., and Nicholson, S.E., 2007: Desertification in the Sahel: A reinterpretation  
24 of a reinterpretation. *Global Change Biology*, **13(7)**, 1308-1313.
- 25 Pringle, C.M., 2001: Hydrologic connectivity and the management of biological reserves: A global perspective.  
26 *Ecological Applications*, **11(4)**, 981-998.
- 27 Prowse, T.D., and Brown, K., 2010: Hydro-ecological effects of changing Arctic river and lake ice covers: a review.  
28 *Hydrology Research*, **41(6)**, 454-461.
- 29 Prugh, L.R., Hodges, K.E., Sinclair, A.R.E., and Brashares, J.S., 2008: Effect of habitat area and isolation on  
30 fragmented animal populations. *Proceedings of the National Academy of Sciences of the United States of*  
31 *America*, **105(52)**, 20770-20775.
- 32 Pulido, F., 2007: Phenotypic changes in spring arrival: evolution, phenotypic plasticity, effects of weather and  
33 condition. *Climate Research*, **35(1-2)**, 5-23.
- 34 Racine, C., Jandt, R., Meyers, C., and Dennis, J., 2004: Tundra fire and vegetation change along a hillslope on the  
35 Seward Peninsula, Alaska, U.S.A. *Arctic, Antarctic, and Alpine Research*, **36(1)**, 1-10.
- 36 Raffa, K.F., Aukema, B.H., Bentz, B.J., Carroll, A.L., Hicke, J.A., Turner, M.G., and Romme, W.H., 2008: Cross-  
37 scale Drivers of Natural Disturbances Prone to Anthropogenic Amplification: The Dynamics of Bark Beetle  
38 Eruptions. *Bioscience*, **58(6)**, 501-517.
- 39 Rahel, F.J., and Olden, J.D., 2008: Assessing the effects of climate change on aquatic invasive species. *Conservation*  
40 *Biology*, **22(3)**, 521-533.
- 41 Randerson, J.T., Liu, H., Flanner, M.G., Chambers, S.D., Jin, Y., Hess, P.G., Pfister, G., Mack, M.C., Treseder,  
42 K.K., Welp, L.R., Chapin, F.S., Harden, J.W., Goulden, M.L., Lyons, E., Neff, J.C., Schuur, E.A.G., and  
43 Zender, C.S., 2006: The impact of boreal forest fire on climate warming. *Science*, **314(5802)**, 1130-1132.
- 44 Randin, C.F., Engler, R., Normand, S., Zappa, M., Zimmermann, N.E., Pearman, P.B., Vittoz, P., Thuiller, W., and  
45 Guisan, A., 2009: Climate change and plant distribution: local models predict high-elevation persistence.  
46 *Global Change Biology*, **15(6)**, 1557-1569.
- 47 Raupach, M.R., Canadell, J.G., and Le Quéré, C., 2008: Anthropogenic and biophysical contributions to  
48 increasing atmospheric CO2 growth rate and airborne fraction. *Biogeosciences*, **5(6)**, 2867-2896.
- 49 Ravi, S., Breshears, D.D., Huxman, T.E., and D'Odorico, P., 2010: Land degradation in drylands: Interactions  
50 among hydrologic-aeolian erosion and vegetation dynamics. *Geomorphology*, **116(3-4)**, 236-245.
- 51 Raxworthy, C.J., Pearson, R.G., Rabibisoa, N., Rakotondrazafy, A.M., Ramanamanjato, J.B., Raselimanana, A.P.,  
52 Wu, S., Nussbaum, R.A., and Stone, D.A., 2008: Extinction vulnerability of tropical montane endemism from  
53 warming and upslope displacement: a preliminary appraisal for the highest massif in Madagascar. *Global*  
54 *Change Biology*, **14(8)**, 1703-1720.

- 1 Ray, D., Nepstad, D., and Moutinho, P., 2005: Micrometeorological and canopy controls of flammability in mature  
2 and disturbed forests in an east-central Amazon landscape. *Ecological Applications*, **15(5)**, 1664-1678.
- 3 Ray, D.K., Ramankutty, N., Mueller, N.D., West, P.C., and Foley, J.A., 2012: Recent patterns of crop yield growth  
4 and stagnation. *Nat Commun*, **3**, 1293.
- 5 Réale, D., McAdam, A.G., Boutin, S., and Berteaux, D., 2003: Genetic and plastic responses of a northern mammal  
6 to climate change. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, **270(1515)**, 591-  
7 596.
- 8 Regnier, C., Fontaine, B., and Bouchet, P., 2009: Not Knowing, Not Recording, Not Listing: Numerous Unnoticed  
9 Mollusk Extinctions. *Conservation Biology*, **23(5)**, 1214-1221.
- 10 Reich, P.B., 2009: Elevated CO2 Reduces Losses of Plant Diversity Caused by Nitrogen Deposition. *Science*,  
11 **326(5958)**, 1399-1402.
- 12 Reist, J.D., Wrona, F.J., Prowse, T.D., Power, M., Dempson, J.B., Beamish, R.J., King, J.R., Carmichael, T.J., and  
13 Sawatzky, C.D., 2006: General effects of climate change on Arctic fishes and fish populations. *Ambio*, **35(7)**,  
14 370-380.
- 15 Renwick, A.R., Massimino, D., Newson, S.E., Chamberlain, D.E., Pearce-Higgins, J.W., and Johnston, A., 2012:  
16 Modelling changes in species' abundance in response to projected climate change. *Diversity and Distributions*,  
17 **18(2)**, 121-132.
- 18 Ricciardi, A., and Simberloff, D., 2009: Assisted colonization is not a viable conservation strategy. *Trends in*  
19 *Ecology & Evolution*, **24(5)**, 248-253.
- 20 Ridgwell, A., Singarayer, J.S., Hetherington, A.M., and Valdes, P.J., 2009: Tackling regional climate change by leaf  
21 albedo bio-geoengineering. *Current Biology*, **19(2)**, 146-150.
- 22 Rieley, J.O., Wüst, R.A.J., Jauhiainen, J., Page, S.E., Wösten, J.H.M., Hooijer, A., Siegert, E., Limin, S.H.,  
23 Vasander, H., and Stahlhut, M., 2008: Tropical peatlands: carbon stores, carbon gas emissions and contribution  
24 to climate change processes. In *Peatlands and climate change* [M. Strack (ed.)]. International Peat Society,  
25 Jyväskylä, pp. 148-181.
- 26 Roberts, S.P.M., Potts, S.G., Biesmeijer, J., Kuhlmann, M., Kunin, B., and Ohlemüller, R., 2011: Assessing  
27 continental-scale risks for generalist and specialist pollinating bee species under climate change. *BioRisk*, **6**, 1-  
28 18.
- 29 Robinet, C., and Roques, A., 2010: Direct impacts of recent climate warming on insect populations. *Integrative*  
30 *Zoology*, **5(2)**, 132-142.
- 31 Rocha, A.V., and Shaver, G.R., 2011: Burn severity influences postfire CO2 exchange in arctic tundra. *Ecological*  
32 *Applications*, **21(2)**, 477-489.
- 33 Rodriguez-Labajos, B., submitted: Climate and change, ecosystems services and costs of action and inaction.  
34 Scoping the interface. *WIREs Climate Change*.
- 35 Rohde, R.F., and Hoffman, M.T., 2012: The historical ecology of Namibian rangelands: Vegetation change since  
36 1876 in response to local and global drivers. *Science of The Total Environment*, **416**, 276-288.
- 37 Romanovsky, V.E., Smith, S.L., and Christiansen, H.H., 2010: Permafrost Thermal State in the Polar Northern  
38 Hemisphere during the International Polar Year 2007-2009: a Synthesis. *Permafrost and Periglacial Processes*,  
39 **21(2)**, 106-116.
- 40 Romijn, E., Herold, M., Kooistra, L., Murdiyarto, D., and Verchot, L., 2012: Assessing capacities of non-Annex I  
41 countries for national forest monitoring in the context of REDD+. *Environmental Science and Policy*, **19-20**,  
42 33-48.
- 43 Rosenheim, J.A., and Tabashnik, B.E., 1991: Influence of generation time on the response to selection. *American*  
44 *Naturalist*, **137(4)**, 527-541.
- 45 Rosset, V., Lehmann, A., and Oertli, B., 2010: Warmer and richer? Predicting the impact of climate warming on  
46 species richness in small temperate waterbodies. *Global Change Biology*, **16(8)**, 2376-2387.
- 47 Rössler, M., 2006: World heritage cultural landscapes: A UNESCO flagship programme 1992-2006. *Landscape*  
48 *Research*, **31(4)**, 333-353.
- 49 Rounsevell, M.D.A., and Reay, D.S., 2009: Land use and climate change in the UK. *Land Use Policy*, **26(0)**, S160-  
50 S169.
- 51 Roux, D.J., Nel, J.L., Ashton, P.J., Deacon, A.R., de Moor, F.C., Hardwick, D., Hill, L., Kleynhans, C.J., Maree,  
52 G.A., Moolman, J., and Scholes, R.J., 2008: Designing protected areas to conserve riverine biodiversity:  
53 Lessons from a hypothetical redesign of the Kruger National Park. *Biological Conservation*, **141(1)**, 100-117.

- 1 Rowe, R.J., Finarelli, J.A., and Rickart, E.A., 2010: Range dynamics of small mammals along an elevational  
2 gradient over an 80-year interval. *Global Change Biology*, **16(11)**, 2930-2943.
- 3 Rubidge, E.M., Monahan, W.B., Parra, J.L., Cameron, S.E., and Brashares, J.S., 2011: The role of climate, habitat,  
4 and species co-occurrence as drivers of change in small mammal distributions over the past century. *Global*  
5 *Change Biology*, **17(2)**, 696-708.
- 6 Ruiz-Labourdette, D., Schmitz, M.F., and Pineda, F.D., 2013: Changes in tree species composition in Mediterranean  
7 mountains under climate change: Indicators for conservation planning. *Ecological Indicators*, **24**, 310-323.
- 8 Rupp, T.S., Chapin, F.S., and Starfield, A., 2001: Modeling the Influence of Topographic Barriers on Treeline  
9 Advance at the Forest-Tundra Ecotone in Northwestern Alaska. *Climatic Change*, **48(2)**, 399-416.
- 10 Rustad, L., 2001: Global change - Matter of time on the prairie. *Nature*, **413(6856)**, 578-579.
- 11 Rustad, L.E., 2008: The response of terrestrial ecosystems to global climate change: Towards an integrated  
12 approach. *Science of the Total Environment*, **404(2-3)**, 222-235.
- 13 Ryan, M.G., Harmon, M.E., Birdsey, R.A., Giardina, C.P., Heath, L.S., Houghton, R.A., Jackson, R.B., McKinley,  
14 D.C., Morrison, J.F., Murray, B.C., Pataki, D.E., and Skog, K.E., 2010: A Synthesis of the Science on Forests  
15 and Carbon for U.S. Forests. *Issues in Ecology*, **13**, 1-17.
- 16 Saatchi, S., Asefi-Najafabady, S., Malhi, Y., Aragão, L.E.O.C., Anderson, L.O., Myneni, R.B., and Nemani, R.,  
17 2013: Persistent effects of a severe drought on Amazonian forest canopy. *Proceedings of the National Academy*  
18 *of Sciences*, **110(2)**, 565-570.
- 19 Saino, N., Rubolini, D., Lehikoinen, E., Sokolov, L.V., Bonisoli-Alquati, A., Ambrosini, R., Boncoraglio, G., and  
20 Moller, A.P., 2009: Climate change effects on migration phenology may mismatch brood parasitic cuckoos and  
21 their hosts. *Biology Letters*, **5(4)**, 539-541.
- 22 Sala, O.E., Parton, W.J., Joyce, L.A., and Lauenroth, W.K., 1988: Primary Production of the Central Grassland  
23 Region of the United States. *Ecology*, **69(1)**, 10-45.
- 24 Salamin, N., Wuest, R.O., Lavergne, S., Thuiller, W., and Pearman, P.B., 2010: Assessing rapid evolution in a  
25 changing environment. *Trends in Ecology & Evolution*, **25(12)**, 692-698.
- 26 Salazar, L.F., Nobre, C.A., and Oyama, M.D., 2007: Climate change consequences on the biome distribution in  
27 tropical South America. *Geophysical Research Letters*, **34(L09708)**, 1-6.
- 28 Salzmann, U., Haywood, A.M., Lunt, D.J., Valdes, P.J., and Hill, D.J., 2008: A new global biome reconstruction  
29 and data-model comparison for the Middle Pliocene. *Global Ecology and Biogeography*, **17(3)**, 432-447.
- 30 Samanta, A., Costa, M.H., Nunes, E.L., Vieira, S.A., Xu, L., and Myneni, R.B., 2011: Comment on "Drought-  
31 Induced Reduction in Global Terrestrial Net Primary Production from 2000 Through 2009". *Science*,  
32 **333(6046)**.
- 33 Sampaio, G., Nobre, C., Costa, M.H., Satyamurty, P., Soares, B.S., and Cardoso, M., 2007: Regional climate change  
34 over eastern Amazonia caused by pasture and soybean cropland expansion. *Geophysical Research Letters*,  
35 **34(L17709)**, 1-7.
- 36 Sandel, B., Arge, L., Dalsgaard, B., Davies, R.G., Gaston, K.J., Sutherland, W.J., and Svenning, J.C., 2011: The  
37 Influence of Late Quaternary Climate-Change Velocity on Species Endemism. *Science*, **334(6056)**, 660-664.
- 38 Sandel, B., and Dangremond, E.M., 2012: Climate change and the invasion of California by grasses. *Global Change*  
39 *Biology*, **18(1)**, 277-289.
- 40 Sankaran, M., Hanan, N.P., Scholes, R.J., Ratnam, J., Augustine, D.J., Cade, B.S., Gignoux, J., Higgins, S.I., Le  
41 Roux, X., Ludwig, F., Ardo, J., Banyikwa, F., Bronn, A., Bucini, G., Caylor, K.K., Coughenour, M.B., Diouf,  
42 A., Ekaya, W., Feral, C.J., February, E.C., Frost, P.G.H., Hiernaux, P., Hrabar, H., Metzger, K.L., Prins,  
43 H.H.T., Ringrose, S., Sea, W., Tews, J., Worden, J., and Zambatis, N., 2005: Determinants of woody cover in  
44 African savannas. *Nature*, **438(7069)**, 846-849.
- 45 Saraux, C., Le Bohec, C., Durant, J.M., Viblanc, V.A., Gauthier-Clerc, M., Beaune, D., Park, Y.-H., Yoccoz, N.G.,  
46 Stenseth, N.C., and Le Maho, Y., 2011: Reliability of flipper-banded penguins as indicators of climate change.  
47 *Nature*, **469(7329)**, 203-206.
- 48 Sarris, D., Christodoulakis, D., and Körner, C., 2011: Impact of recent climatic change on growth of low elevation  
49 eastern Mediterranean forest trees. *Climatic Change*, **106(2)**, 203-223.
- 50 Sato, H., and Ise, T., 2012: Effect of plant dynamic processes on African vegetation responses to climate change:  
51 Analysis using the spatially explicit individual-based dynamic global vegetation model (SEIB-DGVM). *Journal*  
52 *of Geophysical Research-Biogeosciences*, **117**.
- 53 Satterthwaite, D., 2008: Cities' contribution to global warming: notes on the allocation of greenhouse gas emissions.  
54 *Environment and Urbanization*, **20(2)**, 539-549.

- 1 Sauer, J., Domisch, S., Nowak, C., and Haase, P., 2011: Low mountain ranges: summit traps for montane freshwater  
2 species under climate change. *Biodiversity and Conservation*, **20(13)**, 3133-3146.
- 3 Saurral, R.I., Barros, V.R., and Lettenmaier, D.P., 2008: Land use impact on the Uruguay River discharge. *Geophys.*  
4 *Res. Lett.*, **35(12)**, L12401.
- 5 Schaefer, K., Zhang, T.J., Bruhwiler, L., and Barrett, A.P., 2011: Amount and timing of permafrost carbon release in  
6 response to climate warming. *Tellus Series B-Chemical and Physical Meteorology*, **63(2)**, 165-180.
- 7 Schaper, S.V., Dawson, A., Sharp, P.J., Gienapp, P., Caro, S.P., and Visser, M.E., 2012: Increasing Temperature,  
8 Not Mean Temperature, Is a Cue for Avian Timing of Reproduction. *The American Naturalist*, **179(2)**, E55-  
9 E69.
- 10 Scheffer, M., 2009: *Critical transitions in nature and society*. Princeton University Press, Princeton, New Jersey,  
11 400 pp.
- 12 Scheffer, M., Bascompte, J., Brock, W.A., Brovkin, V., Carpenter, S.R., Dakos, V., Held, H., van Nes, E.H.,  
13 Rietkerk, M., and Sugihara, G., 2009: Early-warning signals for critical transitions. *Nature*, **461(7260)**, 53-59.
- 14 Scheffer, M., Hirota, M., Holmgren, M., Van Nes, E.H., and Chapin, F.S., III, 2012: Thresholds for boreal biome  
15 transitions. *Proceedings of the National Academy of Sciences of the United States of America*, **109(52)**, 21384-  
16 21389.
- 17 Scheiter, S., and Higgins, S.I., 2009: Impacts of climate change on the vegetation of Africa: an adaptive dynamic  
18 vegetation modelling approach. *Global Change Biology*, **15(9)**, 2224-2246.
- 19 Schiffers, K., Bourne, E.C., Lavergne, S., Thuiller, W., and Travis, J.M.J., 2013: Limited evolutionary rescue of  
20 locally adapted populations facing climate change. *Philosophical Transactions of the Royal Society B-  
21 Biological Sciences*, **368(1610)**.
- 22 Schippers, P., Verboom, J., Vos, C.C., and Jochem, R., 2011: Metapopulation shift and survival of woodland birds  
23 under climate change: will species be able to track? *Ecography*, **34(6)**, 909-919.
- 24 Schloss, C.A., Nunez, T.A., and Lawler, J.J., 2012: Dispersal will limit ability of mammals to track climate change  
25 in the Western Hemisphere. *Proceedings of the National Academy of Sciences of the United States of America*,  
26 **109(22)**, 8606-8611.
- 27 Schneider, A., Friedl, M.A., and Potere, D., 2009: A new map of global urban extent from MODIS satellite data.  
28 *Environmental Research Letters*, **4(4)**.
- 29 Schnitzler, A., Hale, B.W., and Alsum, E.M., 2007: Examining native and exotic species diversity in European  
30 riparian forests. *Biological Conservation*, **138(1-2)**, 146-156.
- 31 Scholes, R.J., and Archer, S.R., 1997: Tree-grass interactions in savannas. *Annual Review of Ecology and  
32 Systematics*, **28**, 517-544.
- 33 Scholze, M., Knorr, W., Arnell, N.W., and Prentice, I.C., 2006: A climate-change risk analysis for world  
34 ecosystems. *Proceedings of the National Academy of Sciences*, **103(35)**, 13116-13120.
- 35 Schulte, P., Alegret, L., Arenillas, I., Arz, J.A., Barton, P.J., Bown, P.R., Bralower, T.J., Christeson, G.L., Claeys,  
36 P., Cockell, C.S., Collins, G.S., Deutsch, A., Goldin, T.J., Goto, K., Grajales-Nishimura, J.M., Grieve, R.A.F.,  
37 Gulick, S.P.S., Johnson, K.R., Kiessling, W., Koeberl, C., Kring, D.A., MacLeod, K.G., Matsui, T., Melosh, J.,  
38 Montanari, A., Morgan, J.V., Neal, C.R., Nichols, D.J., Norris, R.D., Pierazzo, E., Ravizza, G., Rebolledo-  
39 Vieyra, M., Reimold, W.U., Robin, E., Salge, T., Speijer, R.P., Sweet, A.R., Urrutia-Fucugauchi, J., Vajda, V.,  
40 Whalen, M.T., and Willumsen, P.S., 2010: The Chicxulub Asteroid Impact and Mass Extinction at the  
41 Cretaceous-Paleogene Boundary. *Science*, **327(5970)**, 1214-1218.
- 42 Schultz, M.G., Heil, A., Hoelzemann, J.J., Spessa, A., Thonicke, K., Goldammer, J.G., Held, A.C., Pereira, J.M.C.,  
43 and van het Bolscher, M., 2008: Global wildland fire emissions from 1960 to 2000. *Global Biogeochemical  
44 Cycles*, **22(2)**, 2002.
- 45 Schuur, E.A.G., Bockheim, J., Canadell, J.G., Euskirchen, E., Field, C.B., Goryachkin, S.V., Hagemann, S., Kuhry,  
46 P., Laflour, P.M., Lee, H., Mazhitova, G., Nelson, F.E., Rinke, A., Romanovsky, V.E., Shiklomanov, N.,  
47 Tarnocai, C., Venevsky, S., Vogel, J.G., and Zimov, S.A., 2008: Vulnerability of permafrost carbon to climate  
48 change: Implications for the global carbon cycle. *Bioscience*, **58(8)**, 701-714.
- 49 Schuur, E.A.G., Vogel, J.G., Crummer, K.G., Lee, H., Sickman, J.O., and Osterkamp, T.E., 2009: The effect of  
50 permafrost thaw on old carbon release and net carbon exchange from tundra. *Nature*, **459(7246)**, 556-559.
- 51 Schwaiger, H.P., and Bird, D.N., 2010: Integration of albedo effects caused by land use change into the climate  
52 balance: Should we still account in greenhouse gas units? *Forest Ecology and Management*, **260(3)**, 278-286.
- 53 Schweiger, O., Biesmeijer, J.C., Bommarco, R., Hickler, T., Hulme, P.E., Klotz, S., Kuehn, I., Moora, M., Nielsen,  
54 A., Ohlemüller, R., Petanidou, T., Potts, S.G., Pyšek, P., Stout, J.C., Sykes, M.T., Tscheulin, T., Vila, M.,

- 1 Walther, G.-R., Westphal, C., Winter, M., Zobel, M., and Settele, J., 2010: Multiple stressors on biotic  
2 interactions: how climate change and alien species interact to affect pollination. *Biological Reviews*, **85(4)**, 777-  
3 795.
- 4 Schweiger, O., Harpke, A., Heikkinen, R., Hickler, T., Kühn, I., Pöyry, J., and Settele, J., 2012: Increasing range  
5 mismatching of interacting species under global change is related to their ecological characteristics. *Global  
6 Ecology and Biogeography*, **21(1)**, 88-99.
- 7 Schweiger, O., Settele, J., Kudrna, O., Klotz, S., and Kühn, I., 2008: Climate change can cause spatial mismatch of  
8 trophically interacting species. *Ecology*, **89(12)**, 3472-3479.
- 9 Schwilk, D.W., and Keeley, J.E., 2012: A Plant Distribution Shift: Temperature, Drought or Past Disturbance? *PLoS  
10 One*, **7(2)**.
- 11 Seaquist, J.W., Hickler, T., Eklundh, L., Ardo, J., and Heumann, B.W., 2009: Disentangling the effects of climate  
12 and people on Sahel vegetation dynamics. *Biogeosciences*, **6(3)**, 469-477.
- 13 Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F.X., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., and Yu,  
14 T.H., 2008: Use of US croplands for biofuels increases greenhouse gases through emissions from land-use  
15 change. *Science*, **319(5867)**, 1238-1240.
- 16 Secretariat of the Convention on Biological Diversity, 2010: *Global Biodiversity Outlook 3*. Montréal, 94 pp.
- 17 Seidel, D.J., Fu, Q., Randel, W.J., and Reichler, T.J., 2008: Widening of the tropical belt in a changing climate.  
18 *Nature Geoscience*, **1(1)**, 21-24.
- 19 Sekar, S., 2012: A meta-analysis of the traits affecting dispersal ability in butterflies: can wingspan be used as a  
20 proxy? *Journal of Animal Ecology*, **81(1)**, 174-184.
- 21 Sekercioglu, C.H., Primack, R.B., and Wormworth, J., 2012: The effects of climate change on tropical birds.  
22 *Biological Conservation*, **148(1)**, 1-18.
- 23 Selsted, M.B., van der Linden, L., Ibrom, A., Michelsen, A., Larsen, K.S., Pedersen, J.K., Mikkelsen, T.N.,  
24 Pilegaard, K., Beier, C., and Ambus, P., 2012: Soil respiration is stimulated by elevated CO<sub>2</sub> and reduced by  
25 summer drought: three years of measurements in a multifactor ecosystem manipulation experiment in a  
26 temperate heathland (CLIMAITE). *Global Change Biology*, **18(4)**, 1216-1230.
- 27 Seppälä, R., 2009: A global assessment on adaptation of forests to climate change. *Scandinavian Journal of Forest  
28 Research*, **24(6)**, 469-472.
- 29 Serreze, M.C., and Francis, J.A., 2006: The Arctic amplification debate. *Climate Change*, **76(3)**, 241-264.
- 30 Settele, J., Kudrna, O., Harpke, A., Kühn, I., Van Swaay, C., Verovnik, R., Warren, M., Wiemers, M., Hanspach, J.,  
31 Hickler, T., Kühn, E., Van Halder, I., Veling, K., Vliegthart, A., Wynhoff, I., and Schweiger, O., 2008:  
32 Climatic risk atlas of European butterflies. *BioRisk*, **1**, 1-710.
- 33 Settele, J., and Kühn, E., 2009: Insect Conservation. *Science*, **325(5936)**, 41-42.
- 34 Settele, J., Penev, L., Georgiev, T., Grabaum, R., Grobelnik, V., Hammen, V., Klotz, S., Kotarac, M., and Kühn, I.  
35 (eds.), 2010a: *Atlas of Biodiversity Risk*. Pensoft, Sofia, Moscow, pp. 300.
- 36 Settele, J., Zobel, M., Spangenberg, J.H., Klotz, S., Hammen, V., and Kühn, I., 2010b: Designing Projects for  
37 Integrated Research – The ALARM Experience. In *Atlas of Biodiversity Risk*. Pensoft [J. Settele, L. Penev, T.  
38 Georgiev, R. Grabaum, V. Grobelnik, V. Hammen, S. Klotz, M. Kotarac & I. Kühn (eds.)]. Pensoft, Sofia,  
39 Moscow, pp. 208-209.
- 40 Shanin, V.N., Komarov, A.S., Mikhailov, A.V., and Bykhovets, S.S., 2011: Modelling carbon and nitrogen  
41 dynamics in forest ecosystems of Central Russia under different climate change scenarios and forest  
42 management regimes. *Ecological Modelling*, **222(14)**, 2262-2275.
- 43 Sharma, S., Couturier, S., and Cote, S.D., 2009: Impacts of climate change on the seasonal distribution of migratory  
44 caribou. *Global Change Biology*, **15(10)**, 2549-2562.
- 45 Sharp, B.R., and Bowman, D.M.J.S., 2004: Patterns of long-term woody vegetation change in a sandstone-plateau  
46 savanna woodland, Northern Territory, Australia. *Journal of Tropical Ecology*, **20(03)**, 259-270.
- 47 Shaw, M.R., Pendleton, L., Cameron, D.R., Morris, B., Bachelet, D., Klausmeyer, K., MacKenzie, J., Conklin, D.R.,  
48 Bratman, G.N., Lenihan, J., Haunreiter, E., Daly, C., and Roehrdanz, P.R., 2011: The impact of climate change  
49 on California's ecosystem services. *Climatic Change*, **109(3-4)**, 465-484.
- 50 Shaw, M.R., Zavaleta, E.S., Chiariello, N.R., Cleland, E.E., Mooney, H.A., and Field, C.B., 2002: Grassland  
51 responses to global environmental changes suppressed by elevated CO<sub>2</sub>. *Science*, **298(5600)**, 1987-1990.
- 52 Sheldon, F., Bunn, S.E., Hughes, J.M., Arthington, A.H., Balcombe, S.R., and Fellows, C.S., 2010: Ecological roles  
53 and threats to aquatic refugia in arid landscapes: dryland river waterholes. *Marine and Freshwater Research*,  
54 **61(8)**, 885-895.



- 1 Shimoda, Y., Azim, M.E., Perhar, G., Ramin, M., Kenney, M.A., Sadraddini, S., Gudimov, A., and Arhonditsis,  
2 G.B., 2011: Our current understanding of lake ecosystem response to climate change: What have we really  
3 learned from the north temperate deep lakes? *Journal of Great Lakes Research*, **37(1)**, 173-193.
- 4 Shinoda, M., Nachinshonor, G.U., and Nemoto, M., 2010: Impact of drought on vegetation dynamics of the  
5 Mongolian steppe: A field experiment. *Journal of Arid Environments*, **74(1)**, 63-69.
- 6 Shiogama, H., Emori, S., Hanasaki, N., Abe, M., Masutomi, Y., Takahashi, K., and Nozawa, T., 2011:  
7 Observational constraints indicate risk of drying in the Amazon basin. *Nature Communications*, **2**.
- 8 Silva, L.C.R., and Anand, M., 2013: Probing for the influence of atmospheric CO<sub>2</sub> and climate change on forest  
9 ecosystems across biomes. *Global Ecology and Biogeography*, **22(1)**, 83-92.
- 10 Silva, L.C.R., Anand, M., and Leithead, M.D., 2010: Recent Widespread Tree Growth Decline Despite Increasing  
11 Atmospheric CO<sub>2</sub>. *PLoS One*, **5(7)**, 1-7.
- 12 Silvestrini, R., Soares-Filho, B., Nepstad, D., Coe, M.T., Rodrigues, H., and Assuncao, R., 2011: Simulating fire  
13 regimes in the Amazon in response to climate change and deforestation. *Ecological Applications*, **21(5)**, 1573-  
14 1590.
- 15 Simberloff, D., Martin, J.-L., Genovesi, P., Maris, V., Wardle, D.A., Aronson, J., Courchamp, F., Galil, B., García-  
16 Berthou, E., Pascal, M., Pyšek, P., Sousa, R., Tabacchi, E., and Vilà, M., 2013: Impacts of biological invasions:  
17 what's what and the way forward. *Trends in Ecology & Evolution*, **28(1)**, 58-66.
- 18 Sinervo, B., Mendez-de-la-Cruz, F., Miles, D.B., Heulin, B., Bastiaans, E., Cruz, M.V.S., Lara-Resendiz, R.,  
19 Martinez-Mendez, N., Calderon-Espinosa, M.L., Meza-Lazaro, R.N., Gadsden, H., Avila, L.J., Morando, M.,  
20 De la Riva, I.J., Sepulveda, P.V., Rocha, C.F.D., Iburguengoytia, N., Puntriano, C.A., Massot, M., Lepetz, V.,  
21 Oksanen, T.A., Chapple, D.G., Bauer, A.M., Branch, W.R., Clobert, J., and Sites, J.W., 2010: Erosion of Lizard  
22 Diversity by Climate Change and Altered Thermal Niches. *Science*, **328(5980)**, 894-899.
- 23 Singer, M.C., and Parmesan, C., 2010: Phenological asynchrony between herbivorous insects and their hosts: signal  
24 of climate change or pre-existing adaptive strategy? *Philosophical Transactions of the Royal Society B-  
25 Biological Sciences*, **365(1555)**, 3161-3176.
- 26 Singh, A., Unnikrishnan, S., Naik, N., and Duvvuri, K., 2013: Role of India's forest in climate change mitigation  
27 through the CDM and REDD+. *Journal of Environmental Planning and Management*, **56**, 61-87.
- 28 Sitch, S., Cox, P.M., Collins, W.J., and Huntingford, C., 2007: Indirect radiative forcing of climate change through  
29 ozone effects on the land-carbon sink. *Nature*, **448(7155)**, 791-U794.
- 30 Sitch, S., Huntingford, C., Gedney, N., Levy, P.E., Lomas, M., Piao, S.L., Betts, R., Ciais, P., Cox, P.,  
31 Friedlingstein, P., Jones, C.D., Prentice, I.C., and Woodward, F.I., 2008: Evaluation of the terrestrial carbon  
32 cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation  
33 Models (DGVMs). *Global Change Biology*, **14(9)**, 2015-2039.
- 34 Smallwood, K.S., 2007: Estimating Wind Turbine-Caused Bird Mortality. *Journal of Wildlife Management*, **71(8)**,  
35 2781-2791.
- 36 Smit, B., Burton, I., Klein, R.J.T., and Wandel, J., 2000: An anatomy of adaptation to climate change and variability.  
37 *Climatic Change*, **45(1)**, 223-251.
- 38 Smit, B., Pilifosova, O., Burton, I., Challenger, B., Huq, S., Klein, R.J.T., Yohe, G., Adger, N., Downing, T.,  
39 Harvey, E., Kane, S., Parry, M., Skinner, M., Smith, J., and Wandel, J., 2007: Adaptation to Climate Change in  
40 the Context of Sustainable Development and Equity. In *Third Assessment Report WG II*. Intergovernmental  
41 panel on Climate Change, Geneva, pp. 879-912.
- 42 Smith, A.L., Hewitt, N., Klenk, N., Bazely, D.R., Yan, N., Wood, S., Henriques, I., MacLellan, J.I., and Lipsig-  
43 Mummé, C., 2012: Effects of climate change on the distribution of invasive alien species in Canada: a  
44 knowledge synthesis of range change projections in a warming world. *Environmental Reviews*, **20(1)**, 1-16.
- 45 Smith, L.C., Sheng, Y., MacDonald, G.M., and Hinzman, L.D., 2005: Disappearing Arctic lakes. *Science*,  
46 **308(5727)**, 1429-1429.
- 47 Smol, J.P., and Douglas, M.S.V., 2007a: Crossing the final ecological threshold in high Arctic ponds. *Proceedings  
48 of the National Academy of Sciences of the United States of America*, **104(30)**, 12395-12397.
- 49 Smol, J.P., and Douglas, M.S.V., 2007b: From controversy to consensus: making the case for recent climate using  
50 lake sediments. *Frontiers in Ecology and the Environment*, **5(9)**, 466-474.
- 51 Snyman, H.A., and Fouché, H.J., 1993: Estimating seasonal herbage production of a semi-arid grassland based on  
52 veld condition, rainfall, and evapotranspiration. *African Journal of Range and Forage Science*, **10(1)**, 21-24.

- 1 Soares-Filho, B., Moutinho, P., Nepstad, D., Anderson, A., Rodrigues, H., Garcia, R., Dietzsch, L., Merry, F.,  
2 Bowman, M., Hissa, L., Silvestrini, R., and Maretti, C., 2010: Role of Brazilian Amazon protected areas in  
3 climate change mitigation. *Proceedings of the National Academy of Sciences*, **107(24)**, 10821-10826.
- 4 Soares-Filho, B., Silvestrini, R., Nepstad, D., Brando, P., Rodrigues, H., Alencar, A., Coe, M., Locks, C., Lima, L.,  
5 Hissa, L., and Stickler, C., 2012: Forest fragmentation, climate change and understory fire regimes on the  
6 Amazonian landscapes of the Xingu headwaters. *Landscape Ecology*, **27(4)**, 585-598.
- 7 Sobek-Swant, S., Crosthwaite, J.C., Lyons, D.B., and Sinclair, B.J., 2012: Could phenotypic plasticity limit an  
8 invasive species? Incomplete reversibility of mid-winter deacclimation in emerald ash borer. *Biological*  
9 *Invasions*, **14(1)**, 115-125.
- 10 Sodhi, N.S., Bickford, D., Diesmos, A.C., Lee, T.M., Koh, L.P., Brook, B.W., Sekercioglu, C.H., and Bradshaw,  
11 C.J.A., 2008: Measuring the Meltdown: Drivers of Global Amphibian Extinction and Decline. *PLoS One*, **3(2)**,  
12 8.
- 13 Soja, A.J., Tchepakova, N.M., French, N.H.F., Flannigan, M.D., Shugart, H.H., Stocks, B.J., Sukhinin, A.I.,  
14 Parfenova, E.I., Chapin, F.S., and Stackhouse, P.W., 2007: Climate-induced boreal forest change: Predictions  
15 versus current observations. *Global and Planetary Change*, **56(3-4)**, 274-296.
- 16 Sokolov, L., 2006: Effect of global warming on the timing of migration and breeding of passerine birds in the 20th  
17 century. *Entomological Review Supplement*, **86(1)**, S59-S81.
- 18 Soliani, C., Gallo, L., and Marchelli, P., 2012: Phylogeography of two hybridizing southern beeches (*Nothofagus*  
19 spp.) with different adaptive abilities. *Tree Genetics & Genomes*, **8(4)**, 659-673.
- 20 Sommer, J.H., KrefT, H., Kier, G., Jetz, W., Mutke, J., and Barthlott, W., 2010: Projected impacts of climate change  
21 on regional capacities for global plant species richness. *Proceedings of the Royal Society B-Biological Sciences*,  
22 **277(1692)**, 2271-2280.
- 23 Sovacool, B.K., 2009: Contextualizing avian mortality: A preliminary appraisal of bird and bat fatalities from wind,  
24 fossil-fuel, and nuclear electricity. *Energy Policy*, **32(6)**, 2241-2248.
- 25 Sowerby, A., Emmett, B.A., Tietema, A., and Beier, C., 2008: Contrasting effects of repeated summer drought on  
26 soil carbon efflux in hydric and mesic heathland soils. *Global Change Biology*, **14(10)**, 2388-2404.
- 27 Sowerby, A., Emmett, B.A., Williams, D., Beier, C., and Evans, C.D., 2010: The response of dissolved organic  
28 carbon (DOC) and the ecosystem carbon balance to experimental drought in a temperate shrubland. *European*  
29 *Journal of Soil Science*, **61(5)**, 697-709.
- 30 Stahlschmidt, Z.R., DeNardo, D.F., Holland, J.N., Kotler, B.P., and Kruse-Peebles, M., 2011: Tolerance  
31 mechanisms in North American deserts: Biological and societal approaches to climate change. *Journal of Arid*  
32 *Environments*, **75(8)**, 681-687.
- 33 Staver, A.C., Archibald, S., and Levin, S.A., 2011: The Global Extent and Determinants of Savanna and Forest as  
34 Alternative Biome States. *Science*, **334(6053)**, 230-232.
- 35 Steenberg, J.W.N., Duinker, P.N., and Bush, P.G., 2011: Exploring adaptation to climate change in the forests of  
36 central Nova Scotia, Canada. *Forest Ecology and Management*, **262(12)**, 2316-2327.
- 37 Steffen, W., Persson, A., Deutsch, L., Zalasiewicz, J., Williams, M., Richardson, K., Crumley, C., Crutzen, P.,  
38 Folke, C., Gordon, L., Molina, M., Ramanathan, V., Rockstrom, J., Scheffer, M., Schellnhuber, H.J., and  
39 Svedin, U., 2011: The Anthropocene: From Global Change to Planetary Stewardship. *Ambio*, **40(7)**, 739-761.
- 40 Steffensen, J.P., Andersen, K.K., Bigler, M., Clausen, H.B., Dahl-Jensen, D., Fischer, H., Goto-Azuma, K.,  
41 Hansson, M., Johnsen, S.J., Jouzel, J., Masson-Delmotte, V., Popp, T., Rasmussen, S.O., Rothlisberger, R.,  
42 Ruth, U., Stauffer, B., Siggaard-Andersen, M.L., Sveinbjornsdottir, A.E., Svensson, A., and White, J.W.C.,  
43 2008: High-resolution Greenland Ice Core data show abrupt climate change happens in few years. *Science*,  
44 **321(5889)**, 680-684.
- 45 Stevens, C.J., Dupre, C., Dorland, E., Gaudnik, C., Gowing, D.J.G., Bleeker, A., Diekmann, M., Alard, D., Bobbink,  
46 R., Fowler, D., Corcket, E., Mountford, J.O., Vandvik, V., Aarrestad, P.A., Muller, S., and Dise, N.B., 2010a:  
47 Nitrogen deposition threatens species richness of grasslands across Europe. *Environmental Pollution*, **158(9)**,  
48 2940-2945.
- 49 Stevens, V.M., Turlure, C., and Baguette, M., 2010b: A meta-analysis of dispersal in butterflies. *Biological Reviews*,  
50 **85(3)**, 625-642.
- 51 Stewart, I.T., 2009: Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrological Processes*,  
52 **23(1)**, 78-94.
- 53 Stewart, I.T., Cayan, D.R., and Dettinger, M.D., 2005: Changes toward earlier streamflow timing across western  
54 North America. *Journal of Climate*, **18(8)**, 1136-1155.

- 1 Stewart, J.B., 1988: Modelling surface conductance of pine forest. *Agricultural and Forest Meteorology*. *Agricultural and Forest Meteorology* **43**, 19-35.
- 2
- 3 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.
- 4
- 5
- 6 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.
- 7
- 8
- 9 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.
- 10
- 11 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.
- 12
- 13
- 14 Suarez, F., Binkley, D., Kaye, M.W., and Stottlemeyer, R., 1999: Expansion of forest stands into tundra in the Noatak National Preserve, northwest Alaska. *Ecoscience*, **6(3)**, 465-470.
- 15
- 16 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.
- 17
- 18
- 19 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.
- 20
- 21
- 22 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.
- 23
- 24 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.
- 25
- 26
- 27 Suttle, K.B., Thomsen, M.A., and Power, M.E., 2007: Species Interactions Reverse Grassland Responses to Changing Climate. *Science*, **315(5812)**, 640-642.
- 28
- 29 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.
- 30
- 31
- 32 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.
- 33
- 34
- 35 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.
- 36
- 37
- 38 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.
- 39
- 40 Szlavik, J., and Csete, M., 2012: Climate and Energy Policy in Hungary. *Energies*, **5(2)**, 494-517.
- 41
- 42 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**.
- 43
- 44 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)**.
- 45
- 46 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)**.
- 47
- 48 TEEB, 2009: *TEEB Climate Issues Update*. September 2009, 32-32 pp.
- 49
- 50 Teixeira, 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.
- 51
- 52 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.
- 53
- 54

- 1 Thackeray, S.J., Sparks, T.H., Frederiksen, M., Burthe, S., Bacon, P.J., Bell, J.R., Botham, M.S., Brereton, T.M.,  
2 Bright, P.W., Carvalho, L., Clutton-Brock, T., Dawson, A., Edwards, M., Jones, I.D., Jones, J.T., Leech, D.I.,  
3 Roy, D.B., Scott, W.A., Smith, M., Smithers, R.J., Winfield, I.J., and Wanless, S., 2010: Trophic level  
4 asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. *Global Change  
5 Biology*, **16(12)**, 3304-3313.
- 6 Thaxter, C.B., Joys, A.C., Gregory, R.D., Baillie, S.R., and Noble, D.G., 2010: Hypotheses to explain patterns of  
7 population change among breeding bird species in England. *Biological Conservation*, **143(9)**, 2006-2019.
- 8 The Royal Society, 2008: *Ground-level ozone in the 21st century: future trends, impacts and policy implications*.  
9 London, 132 pp.
- 10 Thomas, C.D., Franco, A.M.A., and Hill, J.K., 2006: Range retractions and extinction in the face of climate  
11 warming. *Trends in Ecology & Evolution*, **21(8)**, 415-416.
- 12 Thompson, P.L., Jacques, M.C., and Vinebrooke, R.D., 2008: Impacts of climate warming and nitrogen deposition  
13 on alpine plankton in lake and pond habitats: an in vitro experiment. *Arctic Antarctic and Alpine Research*,  
14 **40(1)**, 192-198.
- 15 Thonicke, K., Venevsky, S., Sitch, S., and Cramer, W., 2008: The role of fire disturbance for global vegetation  
16 dynamics: coupling fire into a Dynamic Global Vegetation Model. *Global Ecology and Biogeography*, **10**, 661-  
17 667.
- 18 Thornton, P.K., van de Steeg, J., Notenbaert, A., and Herrero, M., 2009: The impacts of climate change on livestock  
19 and livestock systems in developing countries: A review of what we know and what we need to know.  
20 *Agricultural Systems*, **101(3)**, 113-127.
- 21 Thorup, K., Tottrup, A.P., and Rahbek, C., 2007: Patterns of phenological changes in migratory birds. *Oecologia*,  
22 **151(4)**, 697-703.
- 23 Throop, H.L., and Archer, S.R., 2008: Shrub (*Prosopis velutina*) encroachment in a semidesert grassland: spatial-  
24 temporal changes in soil organic carbon and nitrogen pools. *Global Change Biology*, **14(10)**, 2420-2431.
- 25 Thuiller, W., Lavergne, S., Roquet, C., Boulangeat, I., Lafourcade, B., and Araujo, M.B., 2011: Consequences of  
26 climate change on the tree of life in Europe. *Nature*, **470(7335)**, 531-534.
- 27 Thuiller, W., Lavorel, S., Araujo, M.B., Sykes, M.T., and Prentice, I.C., 2005: Climate change threats to plant  
28 diversity in Europe. *Proceedings of the National Academy of Sciences of the United States of America*, **102(23)**,  
29 8245-8250.
- 30 Tilman, D., Balzer, C., Hill, J., and Befort, B.L., 2011: Global food demand and the sustainable intensification of  
31 agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, **108(50)**, 20260-  
32 20264.
- 33 Tingley, M.W., Koo, M.S., Moritz, C., Rush, A.C., and Beissinger, S.R., 2012: The push and pull of climate change  
34 causes heterogeneous shifts in avian elevational ranges. *Global Change Biology*, **18(11)**, 3279-3290.
- 35 Tisseuil, C., Vrac, M., Grenouillet, G., Wade, A.J., Gevrey, M., Oberdorff, T., Grodwohl, J.B., and Lek, S., 2012:  
36 Strengthening the link between climate, hydrological and species distribution modeling to assess the impacts of  
37 climate change on freshwater biodiversity. *Science of the Total Environment*, **424**, 193-201.
- 38 Tng, D.Y.P., Murphy, B.P., Weber, E., Sanders, G., Williamson, G.J., Kemp, J., and Bowman, D.M.J.S., 2012:  
39 Humid tropical rain forest has expanded into eucalypt forest and savanna over the last 50 years. *Ecology and  
40 Evolution*, **2(1)**, 34-45.
- 41 Tockner, K., Bunn, S.E., Gordon, C., Naiman, R.J., Quinn, G.P., and Stanford, J.A., 2008: Floodplains: Critically  
42 threatened ecosystems. In *Aquatic ecosystems. Trends and Global Prospects*. [N. V. C. Polunin (ed.)].  
43 Cambridge Press, Cambridge, pp. 45-61.
- 44 Tol, R.S.J., 2008: The Social Cost of Carbon: Trends, Outliers and Catastrophes. *Economics: The Open-Access,  
45 Open Assessment E-Journal*, **2(2008-25)**.
- 46 Tomppo, E., Gschwantner, T., Lawrence, M., and McRoberts, R.E. (eds.), 2010: *National Forest Inventories -  
47 Pathways for common reporting*. Springer, New York, pp. 612.
- 48 Traill, L.W., Bradshaw, C.J.A., Delean, S., and Brook, B.W., 2010: Wetland conservation and sustainable use under  
49 global change: a tropical Australian case study using magpie geese. *Ecography*, **33(5)**, 818-825.
- 50 Trathan, P.N., Fretwell, P.T., and Stonehouse, B., 2011: First Recorded Loss of an Emperor Penguin Colony in the  
51 Recent Period of Antarctic Regional Warming: Implications for Other Colonies. *PLoS One*, **6(2)**, 1-11.
- 52 Trivedi, M.R., Berry, P.M., Morecroft, M.D., and Dawson, T.P., 2008: Spatial scale affects bioclimate model  
53 projections of climate change impacts on mountain plants. *Global Change Biology*, **14(5)**, 1089-1103.

- 1 Tseng, W.C., and Chen, C.C., 2008: Valuing the potential economic impact of climate change on the Taiwan trout.  
2 *Ecological Economics*, **65(2)**, 282-291.
- 3 Turetsky, M.R., Kane, E.S., Harden, J.W., Ottmar, R.D., Manies, K.L., Hoy, E., and Kasischke, E.S., 2011: Recent  
4 acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. *Nature Geosci*, **4(1)**, 27-31.
- 5 Tylianakis, J.M., Didham, R.K., Bascompte, J., and Wardle, D.A., 2008: Global change and species interactions in  
6 terrestrial ecosystems. *Ecology Letters*, **11(12)**, 1351-1363.
- 7 Uhl, C., and Kauffman, J.B., 1990: Deforestation, fire susceptibility and potential tree responses to fire in the eastern  
8 Amazon. *Ecology*, **71(2)**, 437-449.
- 9 United Nations, Department of Economic and Social Affairs, and Population Division, 2012: *World Urbanization*  
10 *Prospects: The 2011 Revision*. 318 pp.
- 11 Urban, M.C., Leibold, M.A., Amarasekare, P., De Meester, L., Gomulkiewicz, R., Hochberg, M.E., Klausmeier,  
12 C.A., Loeuille, N., de Mazancourt, C., Norberg, J., Pantel, J.H., Strauss, S.Y., Vellend, M., and Wade, M.J.,  
13 2008: The evolutionary ecology of metacommunities. *Trends in Ecology & Evolution*, **23(6)**, 311-317.
- 14 Urban, M.C., Tewksbury, J.J., and Sheldon, K.S., 2012: On a collision course: competition and dispersal differences  
15 create no-analogue communities and cause extinctions during climate change. *Proceedings of the Royal Society*  
16 *B: Biological Sciences*, **279(1735)**, 2072-2080.
- 17 Uys, R.G., Bond, J.W., and Everson, T.M., 2004: The effect of different fire regimes on plant diversity southern  
18 African grasslands. *Biological Conservation*, **118(4)**, 489-499.
- 19 Valdes, P., 2011: Built for stability. *Nature Geoscience*, **4(7)**, 414-416.
- 20 van Asch, M., Salis, L., Holleman, L.J.M., van Lith, B., and Visser, M.E., 2012: Evolutionary response of the egg  
21 hatching date of a herbivorous insect under climate change. *Nature Climate Change*, **advance online**  
22 **publication**.
- 23 van Asch, M., Tienderen, P.H., Holleman, L.J.M., and Visser, M.E., 2007: Predicting adaptation of phenology in  
24 response to climate change, an insect herbivore example. *Global Change Biology*, **13(8)**, 1596-1604.
- 25 van Asch, M., and Visser, M.E., 2007: Phenology of Forest Caterpillars and Their Host Trees: The Importance of  
26 Synchrony. *Annual Review of Entomology*, **52**, 37-55.
- 27 Van Auken, O.W., 2009: Causes and consequences of woody plant encroachment into western North American  
28 grasslands. *Journal of Environmental Management*, **90(10)**, 2931-2942.
- 29 van der Linde, J.A., Six, D.L., Wingfield, M.J., and Roux, J., 2011: Lasiodiplodia species associated with dying  
30 Euphorbia ingens in South Africa. *Southern Forests: a Journal of Forest Science*, **73(3-4)**, 165-173.
- 31 van der Molen, M.K., van den Hurk, B.J.J.M., and Hazeleger, W., 2011: A dampened land use change climate  
32 response towards the tropics. *Climate Dynamics*, **37(9-10)**, 2035-2043.
- 33 van der Werf, G.R., Randerson, J.T., Giglio, L., Collatz, G.J., Mu, M., Kasibhatla, P.S., Morton, D.C., DeFries,  
34 R.S., Jin, Y., and van Leeuwen, T.T., 2010: Global fire emissions and the contribution of deforestation,  
35 savanna, forest, agricultural, and peat fires (1997–2009). *Atmos. Chem. Phys*, **223**, 11-707.
- 36 Van Herk, I.G., Gower, S.T., Bronson, D.R., and Tanner, M.S., 2011: Effects of climate warming on canopy water  
37 dynamics of a boreal black spruce plantation. *Canadian Journal of Forest Research-Revue Canadienne De*  
38 *Recherche Forestiere*, **41(2)**, 217-227.
- 39 van Kleunen, M., Weber, E., and Fischer, M., 2010: A meta-analysis of trait differences between invasive and non-  
40 invasive plant species. *Ecology Letters*, **13(2)**, 235-245.
- 41 van Mantgem, P.J., Stephenson, N.L., Byrne, J.C., Daniels, L.D., Franklin, J.F., Fule, P.Z., Harmon, M.E., Larson,  
42 A.J., Smith, J.M., Taylor, A.H., and Veblen, T.T., 2009: Widespread Increase of Tree Mortality Rates in the  
43 Western United States. *Science*, **323(5913)**, 521-524.
- 44 van Vliet, M.T.H., Ludwig, F., Zwolsman, J.J.G., Weedon, G.P., and Kabat, P., 2011: Global river temperatures and  
45 sensitivity to atmospheric warming and changes in river flow. *Water Resources Research*, **47(W02544)**, 1-19.
- 46 van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V.,  
47 Lamarque, J.-F., Masui, T., Nakicenovic, N., Smith, S.J., and Rose, S.K., 2011: The representative  
48 concentration pathways: an overview. *Climatic Change*, **109**, 5–31.
- 49 van Wilgen, B.W., and Richardson, D.M., 2012: Three centuries of managing introduced conifers in South Africa:  
50 Benefits, impacts, changing perceptions and conflict resolution. *Journal of Environmental Management*, **106**,  
51 56-68.
- 52 Veldman, J.W., and Putz, F.E., 2011: Grass-dominated vegetation, not species-diverse natural savanna, replaces  
53 degraded tropical forests on the southern edge of the Amazon Basin. *Biological Conservation*, **144(5)**, 1419-  
54 1429.

- 1 Vennetier, M., and Ripert, C., 2010: Climate change impact on vegetation: lessons from an exceptionally hot and  
2 dry decade in south-eastern France. *Climate change and variability*.
- 3 Verburg, P., Hecky, R.E., and Kling, H., 2003: Ecological consequences of a century of warming in Lake  
4 Tanganyika. *Science*, **301(5632)**, 505-507.
- 5 Viglizzo, E.F., Frank, F.C., Carreno, L.V., Jobbagy, E.G., Pereyra, H., Clatt, J., Pincen, D., and Ricard, M.F., 2011:  
6 Ecological and environmental footprint of 50 years of agricultural expansion in Argentina. *Global Change  
7 Biology*, **17(2)**, 959-973.
- 8 Vilà-Cabrera, A., Martínez-Vilalta, J., Galiano, L., and Retana, J., 2012: Patterns of Forest Decline and  
9 Regeneration Across Scots Pine Populations. *Ecosystems*, 1-13.
- 10 Viles, H.A., and Cutler, N.A., 2012: Global environmental change and the biology of heritage structures. *Global  
11 Change Biology*, **online early**.
- 12 Vinukollu, R.K., Meynadier, R., Sheffield, J., and Wood, E.F., 2011: Multi-model, multi-sensor estimates of global  
13 evapotranspiration: climatology, uncertainties and trends. *Hydrol. Process.*, **5**, 3993-4010.
- 14 Visser, M.E., and Both, C., 2005: Shifts in phenology due to global climate change: the need for a yardstick.  
15 *Proceedings of the Royal Society of London Series B - Biological Sciences*, **272(1665)**, 2561-2569.
- 16 Visser, M.E., Holleman, L.J.M., and Caro, S.P., 2009: Temperature has a causal effect on avian timing of  
17 reproduction. *Proceedings of the Royal Society B: Biological Sciences*, **276(1665)**, 2323-2331.
- 18 Vitt, P., Havens, K., and Hoegh-Guldberg, O., 2009: Assisted migration: part of an integrated conservation strategy.  
19 *Trends in Ecology & Evolution*, **24(9)**, 473-474.
- 20 Vitt, P., Havens, K., Kramer, A.T., Sollenberger, D., and Yates, E., 2010: Assisted migration of plants: Changes in  
21 latitudes, changes in attitudes. *Biological Conservation*, **143(1)**, 18-27.
- 22 Vittoz, P., Randin, C., Dutoit, A., Bonnet, F., and Hegg, O., 2009: Low impact of climate change on subalpine  
23 grasslands in the Swiss Northern Alps. *Global Change Biology*, **15(1)**, 209-220.
- 24 Vohland, K., and Barry, B., 2009: A review of in situ rainwater harvesting (RWH) practices modifying landscape  
25 functions in African drylands. *Agriculture Ecosystems & Environment*, **131(3-4)**, 119-127.
- 26 Vongraven, D., and Richardson, E., 2011: Biodiversity - Status and Trends of Polar Bears. *Arctic Report Card:  
27 Update for 2011, 2012*, from [www.arctic.noaa.gov/reportcard/biodiv\\_polar\\_bears.html](http://www.arctic.noaa.gov/reportcard/biodiv_polar_bears.html).
- 28 Vörösmarty, C.J., Green, P., Salisbury, J., and Lammers, R.B., 2000: Global water resources: Vulnerability from  
29 climate change and population growth. *Science*, **289(5477)**, 284-288.
- 30 Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E.,  
31 Sullivan, C.A., Liermann, C.R., and Davies, P.M., 2010: Global threats to human water security and river  
32 biodiversity (vol 467, pg 555, 2010). *Nature*, **468(7321)**, 334-334.
- 33 Vredenburg, V.T., Knapp, R.A., Tunstall, T.S., and Briggs, C.J., 2010: Dynamics of an emerging disease drive  
34 large-scale amphibian population extinctions. *Proceedings of the National Academy of Sciences of the United  
35 States of America*, **107(21)**, 9689-9694.
- 36 Wagner, C., and Adrian, R., 2009: Cyanobacteria dominance: Quantifying the effects of climate change. *Limnology  
37 and Oceanography*, **54(6)**, 2460-2468.
- 38 Wake, D.B., 2012: Facing Extinction in Real Time. *Science*, **335(6072)**, 1052-1053.
- 39 Walker, B., Holling, C.S., Carpenter, S.R., and Kinzig, A., 2004: Resilience, adaptability and transformability in  
40 social-ecological systems. *9(2): 5. Ecology and Society*, **9(2)**, 5.
- 41 Walker, B.H., and Langridge, J.L., 1997: Predicting savanna vegetation structure on the basis of plant available  
42 moisture (PAM) and plant available nutrients (PAN): A case study from Australia. *Journal of Biogeography*,  
43 **24**, 813-825.
- 44 Walker, B.H., and Salt, D., 2006: *Resilience Thinking: Sustaining Ecosystems And People In A Changing World*.  
45 Island Press, Washington, DC, 174 pp.
- 46 Walker, D.A., Epstein, H.E., Raynolds, M.K., Kuss, P., Kopecky, M.A., Frost, G.V., Daniels, F.J.A., Leibman,  
47 M.O., Moskalenko, N.G., Matyshak, G.V., Khitun, O.V., Khomutov, A.V., Forbes, B.C., Bhatt, U.S., Kade,  
48 A.N., Vonlanthen, C.M., and Tichy, L., 2012: Environment, vegetation and greenness (NDVI) along the North  
49 America and Eurasia Arctic transects. *Environmental Research Letters*, **7(1)**.
- 50 Walker, M.W.C., Hollister RD, Henry GHR, Ahlquist LE, Alatalo JM, Bret-Harte MS, Calef MP, Callaghan TV,  
51 Carroll AB, Epstein HE, Jonsdottir IS, Klein JA, Magnusson B, Molau U, Oberbauer SF, Rewa SP, Robinson  
52 CH, Shaver GR, Suding KN, Thompson CC, Tolvanen A, Totland O, Turner PL, Tweedie CE, Webber PJ,  
53 Wookey PA, 2006: Plant community responses to experimental warming across the tundra biome. *Proceedings  
54 of the National Academy of Sciences of the United States of America*, **103(5)**, 1342-1346.

- 1 Walter, J., Grant, K., Beierkuhnlein, C., Kreyling, J., Weber, M., and Jentsch, A., 2012: Increased rainfall variability  
2 reduces biomass and forage quality of temperate grassland largely independent of mowing frequency.  
3 *Agriculture Ecosystems & Environment*, **148**, 1-10.
- 4 Walters, R.J., Blanckenhorn, W.U., and Berger, D., 2012: Forecasting extinction risk of ectotherms under climate  
5 warming: an evolutionary perspective. *Functional Ecology*, **26(6)**, 1324-1338.
- 6 Walther, G.-R., Berger, S., and Sykes, M.T., 2005: An ecological 'footprint' of climate change. *Proceedings of the*  
7 *Royal Society B: Biological Sciences*, **272(1571)**, 1427-1432.
- 8 Walther, G.-R., Roques, A., Hulme, P.E., Sykes, M.T., Pysek, P., Kuehn, I., Zobel, M., Bacher, S., Botta-Dukat, Z.,  
9 Bugmann, H., Czucz, B., Dauber, J., Hickler, T., Jarosik, V., Kenis, M., Klotz, S., Minchin, D., Moora, M.,  
10 Nentwig, W., Ott, J., Panov, V.E., Reineking, B., Robinet, C., Semchenko, V., Solarz, W., Thuiller, W., Vila,  
11 M., Vohland, K., and Settele, J., 2009: Alien species in a warmer world: risks and opportunities. *Trends in*  
12 *Ecology & Evolution*, **24(12)**, 686-693.
- 13 Wang, B., Huang, J., Yang, X., Zhang, B., and Liu, M., 2010a: Estimation of biomass, net primary production and  
14 net ecosystem production of China's forests based on the 1999–2003 National Forest Inventory. *Scandinavian*  
15 *Journal of Forest Research*, **25(6)**, 544-553.
- 16 Wang, K., Dickinson, E.D., Wild, M., and Liang, S., 2010b: Evidence for decadal variation in global terrestrial  
17 evapotranspiration between 1982 and 2002. *Journal of Geophysical Research*, **115(D20133)**.
- 18 Ward, D., 2005: Do we understand the causes of bush encroachment in African savannas? *African Journal of Range*  
19 *and Forage Science*, **22(2)**, 101-105.
- 20 Wardle, P., and Coleman, M.C., 1992: Evidence for rising upper limits of four native New Zealand forest trees. *New*  
21 *Zealand Journal of Botany*, **30(3)**, 303-314.
- 22 Warren, R., Price, J., Fischlin, A., Santos, S.D., and Midgley, G., 2011: Increasing impacts of climate change upon  
23 ecosystems with increasing global mean temperature rise. *Climatic Change*, **106(2)**, 141-177.
- 24 Warszawski, L., Friend, A., Ostberg, S., Frieler, K., Lucht, W., Schaphoff, S., and Beerling, D., Risk of ecosystem  
25 shift under climate change, a multi-model analysis. *Proceeding of the National Academy of Science*, submitted.
- 26 Watkiss, P., and Downing, T., 2008: The social cost of carbon: Valuation estimates and their use in UK policy.  
27 *Integrated Assessment*, **8(1)**, 85-105.
- 28 Watrin, J., Lezine, A.M., and Hely, C., 2009: Plant migration and plant communities at the time of the "green  
29 Sahara". *Comptes Rendus Geoscience*, **341(8-9)**, 656-670.
- 30 Wearn, O.R., Reuman, D.C., and Ewers, R.M., 2012: Extinction Debt and Windows of Conservation Opportunity in  
31 the Brazilian Amazon. *Science*, **337(6091)**, 228-232.
- 32 Webb, B.W., and Nobilis, F., 2007: Long-term changes in river temperature and the influence of climatic and  
33 hydrological factors. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques*, **52(1)**, 74-85.
- 34 Welp, L.R., Randerson, J.T., and Liu, H.P., 2007: The sensitivity of carbon fluxes to spring warming and summer  
35 drought depends on plant functional type in boreal forest ecosystems. *Agricultural and Forest Meteorology*,  
36 **147(3-4)**, 172-185.
- 37 Weng, E.S., and Zhou, G.S., 2006: Modeling distribution changes of vegetation in China under future climate  
38 change. *Environmental Modeling & Assessment*, **11(1)**, 45-58.
- 39 West, J., Julius, S.H., Kareiva, P., Enquist, C., Lawler, J.J., Petersen, B., Johnson, A.E., and Shaw, M.R., 2009: U.S.  
40 Natural Resources and Climate Change: Concepts and Approaches for Management Adaptation. *Environmental*  
41 *Management*, **44(6)**, 1001-1021.
- 42 West, J.S., Townsend, J.A., Stevens, M., and Fitt, B.D.L., 2012: Comparative biology of different plant pathogens to  
43 estimate effects of climate change on crop diseases in Europe. *European Journal of Plant Pathology*, **133(1)**,  
44 315-331.
- 45 Westerling, A., Hidalgo, H., Cayan, D., and Swetnam, T., 2006: Warming and earlier spring increase western US  
46 forest wildfire activity. *Science*, **313(5887)**, 940-943.
- 47 Westerling, A.L., Turner, M.G., Smithwick, E.A.H., Romme, W.H., and Ryan, M.G., 2011: Continued warming  
48 could transform Greater Yellowstone fire regimes by mid-21st century. *Proceedings of the National Academy of*  
49 *Sciences of the USA 108: 13 165-13 170*, **108(13)**, 165-113 170.
- 50 Westley, F., Olsson, P., Folke, C., Homer-Dixon, T., Vredenburg, H., Loorbach, D., Thompson, J., Nilsson, M.,  
51 Lambin, E., Sendzimir, J., Banerjee, B., Galaz, V., and van der Leeuw, S., 2011: Tipping Toward  
52 Sustainability: Emerging Pathways of Transformation. *Ambio*, **40(7)**, 762-780.
- 53 White, M.A., de Beurs, K.M., Didan, K., Inouye, D.W., Richardson, A.D., Jensen, O.P., O'Keefe, J., Zhang, G.,  
54 Nemani, R.R., van Leeuwen, W.J.D., Brown, J.F., de Wit, A., Schaepman, M., Lin, X.M., Dettinger, M.,

- 1 Bailey, A.S., Kimball, J., Schwartz, M.D., Baldocchi, D.D., Lee, J.T., and Lauenroth, W.K., 2009:  
2 Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote  
3 sensing for 1982-2006. *Global Change Biology*, **15(10)**, 2335-2359.
- 4 Wickham, J.D., Wade, T.G., and Riitters, K.H., 2012: Empirical analysis of the influence of forest extent on annual  
5 and seasonal surface temperatures for the continental United States. *Global Ecology and Biogeography*, n/a-n/a.
- 6 Wiedner, C., Rucker, J., Bruggemann, R., and Nixdorf, B., 2007: Climate change affects timing and size of  
7 populations of an invasive cyanobacterium in temperate regions. *Oecologia*, **152(3)**, 473-484.
- 8 Wiegand, K., Ward, D., and Saltz, D., 2005: Multi-scale patterns and bush encroachment in an arid savanna with a  
9 shallow soil layer. *Journal of Vegetation Science*, **16(3)**, 311-320.
- 10 Wiens, J.A., Seavy, N.E., and Jongsomjit, D., 2011: Protected areas in climate space: What will the future bring?  
11 *Biological Conservation*, **144(8)**, 2119-2125.
- 12 Wigley, B.J., Bond, W.J., and Hoffman, M.T., 2009: Bush encroachment under three contrasting land-use practices  
13 in a mesic South African savanna. *African Journal of Ecology*, **47(s1)**, 62-70.
- 14 Wiley, M.J., Hyndman, D.W., Pijanowski, B.C., Kendall, A.D., Riseng, C., Rutherford, E.S., Cheng, S.T., Carlson,  
15 M.L., Tyler, J.A., Stevenson, R.J., Steen, P.J., Richards, P.L., Seelbach, P.W., Koches, J.M., and Rediske, R.R.,  
16 2010: A multi-modeling approach to evaluating climate and land use change impacts in a Great Lakes River  
17 Basin. *Hydrobiologia*, **657(1)**, 243-262.
- 18 Wilkinson, S., and Davies, W.J., 2010: Drought, ozone, ABA and ethylene: new insights from cell to plant to  
19 community. *Plant Cell and Environment*, **33(4)**, 510-525.
- 20 Williams, A.L., Wills, K.E., Janes, J.K., Schoor, J.K.V., Newton, P.C.D., and Hovenden, M.J., 2007a: Warming and  
21 free-air CO<sub>2</sub> enrichment alter demographics in four co-occurring grassland species. *New Phytologist*, **176(2)**,  
22 365-374.
- 23 Williams, A.P., Allen, C.D., Macalady, A.K., Griffin, D., Woodhouse, C.A., Meko, D.M., Swetnam, T.W.,  
24 Rauscher, S.A., Seager, R., Grissino-Mayer, H.D., Dean, J.S., Cook, E.R., Gangodagamage, C., Cai, M., and  
25 McDowell, N.G., 2012: Temperature as a potent driver of regional forest drought stress and tree mortality.  
26 *Nature Clim. Change*, **advance online publication**.
- 27 Williams, A.P., Allen, C.D., Millar, C.I., Swetnam, T.W., Michaelsen, J., Still, C.J., and Leavitt, S.W., 2010a:  
28 Forest responses to increasing aridity and warmth in the southwestern United States. *Proceedings of the*  
29 *National Academy of Sciences of the United States of America*, **107(50)**, 21289-21294.
- 30 Williams, J.W., Blois, J.L., and Shuman, B.N., 2011: Extrinsic and intrinsic forcing of abrupt ecological change:  
31 case studies from the late Quaternary. *Journal of Ecology*, **99(3)**, 664-677.
- 32 Williams, J.W., and Jackson, S.T., 2007: Novel climates, no-analog communities, and ecological surprises.  
33 *Frontiers in Ecology and the Environment*, **5(9)**, 475-482.
- 34 Williams, J.W., Jackson, S.T., and Kutzbach, J.E., 2007b: Projected distributions of novel and disappearing  
35 climates by 2100 AD. *Proceedings of the National Academy of Sciences of the United States of America*,  
36 **104(14)**, 5738-5742.
- 37 Williams, J.W., Shuman, B., and Bartlein, P.J., 2009: Rapid responses of the prairie-forest ecotone to early  
38 Holocene aridity in mid-continental North America. *Global and Planetary Change*, **66(3-4)**, 195-207.
- 39 Williams, J.W., Shuman, B., Bartlein, P.J., Diffenbaugh, N.S., and Webb, T., 2010b: Rapid, time-transgressive, and  
40 variable responses to early Holocene midcontinental drying in North America. *Geology*, **38(2)**, 135-138.
- 41 Willis, C.G., Ruhfel, B.R., Primack, R.B., Miller-Rushing, A.J., Losos, J.B., and Davis, C.C., 2010a: Favorable  
42 Climate Change Response Explains Non-Native Species' Success in Thoreau's Woods. *PLoS One*, **5(1)**, 1-5.
- 43 Willis, C.K.R., Barclay, R.M.R., Boyles, J.G., Brigham, R.M., Brack Jr, V., Waldien, D.L., and Reichard, J., 2010b:  
44 Bats are not birds and other problems with Sovacool's (2009) analysis of animal fatalities due to electricity  
45 generation. *Energy Policy*, **38**, 2067-2069.
- 46 Willis, K.J., Bennett, K.D., Bhagwat, S.A., and Birks, H.J.B., 2010c: 4 °C and beyond: what did this mean for  
47 biodiversity in the past? *Systematics and Biodiversity*, **8(1)**, 3-9.
- 48 Willis, K.J., and Bhagwat, S.A., 2009: Biodiversity and Climate Change. *Science*, **326(5954)**, 806-807.
- 49 Willis, K.J., and MacDonald, G.M., 2011: Long-Term Ecological Records and Their Relevance to Climate Change  
50 Predictions for a Warmer World. In *Annual Review of Ecology, Evolution, and Systematics*, Vol 42 [D. J.  
51 Futuyama, H. B. Shaffer & D. Simberloff (eds.)]. pp. 267-287.
- 52 Wilson, R., D'Arrigo, R., Buckley, B., BÃ¼ntgen, U., Esper, J., Frank, D., Luckman, B., Payette, S., Vose, R., and  
53 Youngblut, D., 2007: A matter of divergence: Tracking recent warming at hemispheric scales using tree ring  
54 data. *Journal of Geophysical Research - Atmospheres*, **112(D17103)**, 1-17.



- 1 Winder, M., Jassby, A.D., and Mac Nally, R., 2011: Synergies between climate anomalies and hydrological  
2 modifications facilitate estuarine biotic invasions. *Ecology Letters*, **14(8)**, 749-757.
- 3 Winder, M., and Schindler, D.E., 2004: Climatic effects on the phenology of lake processes. *Global Change*  
4 *Biology*, **10(11)**, 1844-1856.
- 5 Wing, S.L., Harrington, G.J., Smith, F.A., Bloch, J.I., Boyer, D.M., and Freeman, K.H., 2005: Transient floral  
6 change and rapid global warming at the Paleocene-Eocene boundary. *Science*, **310(5750)**, 993-996.
- 7 Winter, M., Schweiger, O., Klotz, S., Nentwig, W., Andriopoulos, P., Arianoutsou, M., Basnou, C., Delipetrou, P.,  
8 Didziulis, V., Hejda, M., Hulme, P.E., Lambdon, P.W., Pergl, J., Pyšek, P., Roy, D.B., and Kühn, I., 2009: Plant  
9 extinctions and introductions lead to phylogenetic and taxonomic homogenization of the European flora.  
10 *Proceedings of the National Academy of Sciences of the United States of America*, **106(51)**, 21721-21725.
- 11 Wise, M., Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R., Smith, S.J., Janetos, A., and  
12 Edmonds, J., 2009: Implications of Limiting CO<sub>2</sub> Concentrations for Land Use and Energy. *Science*,  
13 **324(5931)**, 1183-1186.
- 14 Witt, G.B., Harrington, R.A., and Page, M.J., 2009: Is 'vegetation thickening' occurring in Queensland's mulga  
15 lands – a 50-year aerial photographic analysis. *Australian Journal of Botany*, **57(7)**, 572-582.
- 16 Witte, J.C., Douglass, A.R., da Silva, A., Torres, O., Levy, R., and Duncan, B.N., 2011: NASA A-Train and Terra  
17 observations of the 2010 Russian wildfires. *Atmospheric Chemistry and Physics*, **11(17)**, 9287-9301.
- 18 Wittig, V.E., Ainsworth, E.A., and Long, S.P., 2007: To what extent do current and projected increases in surface  
19 ozone affect photosynthesis and stomatal conductance of trees? A meta-analytic review of the last 3 decades of  
20 experiments. *Plant, Cell & Environment*, **30(9)**, 1150-1162.
- 21 Wittig, V.E., Ainsworth, E.A., Naidu, S.L., Karnosky, D.F., and Long, S.P., 2009: Quantifying the impact of current  
22 and future tropospheric ozone on tree biomass, growth physiology and biochemistry. *Global Change Biology*,  
23 **15(2)**, 396-424.
- 24 Wolken, J.M., Hollingsworth, T.N., Rupp, T.S., Chapin, F.S., Trainor, S.F., Barrett, T.M., Sullivan, P.F., McGuire,  
25 A.D., Euskirchen, E.S., Hennon, P.E., Beever, E.A., Conn, J.S., Crone, L.K., D'Amore, D.V., Fresco, N.,  
26 Hanley, T.A., Kielland, K., Kruse, J.J., Patterson, T., Schuur, E.A.G., Verbyla, D.L., and Yarie, J., 2011:  
27 Evidence and implications of recent and projected climate change in Alaska's forest ecosystems. *Ecosphere*,  
28 **2(11)**, art124.
- 29 Wolkovich, E.M., Cook, B.I., Allen, J.M., Crimmins, T.M., Betancourt, J.L., Travers, S.E., Pau, S., Regetz, J.,  
30 Davies, T.J., Kraft, N.J.B., Ault, T.R., Bolmgren, K., Mazer, S.J., McCabe, G.J., McGill, B.J., Parmesan, C.,  
31 Salamin, N., Schwartz, M.D., and Cleland, E.E., 2012: Warming experiments underpredict plant phenological  
32 responses to climate change. *Nature*, **advance online publication**, 1-4.
- 33 Wood, T.E., Cavaleri, M.A., and Reed, S.C., 2012: Tropical forest carbon balance in a warmer world: a critical  
34 review spanning microbial- to ecosystem-scale processes. *Biological Reviews*, **87(4)**, 912-927.
- 35 Woodburne, M.O., Gunnell, G.F., and Stucky, R.K., 2009: Climate directly influences Eocene mammal faunal  
36 dynamics in North America. *Proceedings of the National Academy of Sciences of the United States of America*,  
37 **106(32)**, 13399-13403.
- 38 Worrall, J.J., Rehfeldt, G.E., Hamann, A., Hogg, E.H., Marchetti, S.B., Michaelian, M., and Gray, L.K., 2013:  
39 Recent declines of *Populus tremuloides* in North America linked to climate. *Forest Ecology and Management*.
- 40 Wu, C.Y., and Chen, J.M., 2013: Diverse responses of vegetation production to interannual summer drought in  
41 North America. *International Journal of Applied Earth Observation and Geoinformation*, **21**, 1-6.
- 42 Wu, X.B., and Archer, S.R., 2005: Scale-dependent influence of topography-based hydrologic features on patterns  
43 of woody plant encroachment in savanna landscapes. *Landscape Ecology*, **20(6)**, 733-742.
- 44 Wu, Z., Zhang, H., Krause, C.M., and Cobb, N.S., 2010: Climate change and human activities: a case study in  
45 Xinjiang, China. *Climatic Change*, **99(3-4)**, 457-472.
- 46 Xenopoulos, M.A., Lodge, D.M., Alcamo, J., Marker, M., Schulze, K., and Van Vuuren, D.P., 2005: Scenarios of  
47 freshwater fish extinctions from climate change and water withdrawal. *Global Change Biology*, **11(10)**, 1557-  
48 1564.
- 49 Xu, L., Myneni, R.B., Chapin III, F.S., Callaghan, T.V., Pinzon, J.E., Tucker, C.J., Zhu, Z., Bi, J., Ciais, P.,  
50 Tømmervik, H., Euskirchen, E.S., Forbes, B.C., Piao, S.L., Anderson, B.T., Ganguly, S., Nemani, R.R., Goetz,  
51 S.J., Beck, P.S.A., Bunn, A.G., Cao, C., and Stroeve, J.C., 2013: Diminished temperature and vegetation  
52 seasonality over northern high latitudes. *Nature Climate Change*, in press.
- 53 Yi, S.H., Woo, M.K., and Arain, M.A., 2007: Impacts of peat and vegetation on permafrost degradation under  
54 climate warming. *Geophysical Research Letters*, **34(16)**.

- 1 Yoshikawa, S., and Sanga-Ngoie, K., 2011: Deforestation dynamics in Mato Grosso in the southern Brazilian  
2 Amazon using GIS and NOAA/AVHRR data. *International Journal of Remote Sensing*, **32(2)**, 523-544.
- 3 Yvon-Durocher, G., Montoya, J.M., Trimmer, M., and Woodward, G., 2011: Warming alters the size spectrum and  
4 shifts the distribution of biomass in freshwater ecosystems. *Global Change Biology*, **17(4)**, 1681-1694.
- 5 Zavaleta, E.S., Shaw, M.R., Chiariello, N.R., Thomas, B.D., Cleland, E.E., Field, C.B., and Mooney, H.A., 2003a:  
6 Grassland responses to three years of elevated temperature, CO<sub>2</sub>, precipitation, and N deposition. *Ecological*  
7 *Monographs*, **73(4)**, 585-604.
- 8 Zavaleta, E.S., Thomas, B.D., Chiariello, N.R., Asner, G.P., Shaw, M.R., and Field, C.B., 2003b: Plants reverse  
9 warming effect on ecosystem water balance. *Proceedings of the National Academy of Sciences of the United*  
10 *States of America*, **100(17)**, 9892-9893.
- 11 Zelazowski, P., Malhi, Y., Huntingford, C., Sitch, S., and Fisher, J.B., 2011: Changes in the potential distribution of  
12 humid tropical forests on a warmer planet. *Philosophical Transactions of the Royal Society A: Mathematical,*  
13 *Physical and Engineering Sciences*, **369(1934)**, 137-160.
- 14 Zeng, Z., Piao, S., Lin, X., Yin, G., Peng, S., Ciais, P., and Myneni, R.B., 2012: Global evapotranspiration over the  
15 past three decades: estimation based on the water balance equation combined with empirical models.  
16 *Environmental Research Letters*, **7**.
- 17 Zerebecki, R.A., and Sorte, C.J.B., 2011: Temperature Tolerance and Stress Proteins as Mechanisms of Invasive  
18 Species Success. *PLoS One*, **6(4)**, 1-7.
- 19 Zhang, H., Li, Y., and Gao, X., 2009: Potential impacts of land-use on climate variability and extremes. *Advances in*  
20 *Atmospheric Sciences*, **26(5)**, 840-854.
- 21 Zhang, Y.Y., Fischer, M., Colot, V., and Bossdorf, O., 2013: Epigenetic variation creates potential for evolution of  
22 plant phenotypic plasticity. *New Phytologist*, **197(1)**, 314-322.
- 23 Zhao, M., and Running, S.W., 2010: Drought-induced reduction in global terrestrial net primary production from  
24 2000 through 2009. *Science*, **329(5994)**, 940-943.
- 25 Zhou, G., Peng, C., Li, Y., Liu, S., Zhang, Q., Tang, X., Liu, J., Yan, J., Zhang, D., and Chu, G., 2013: A climate  
26 change-induced threat to the ecological resilience of a subtropical monsoon evergreen broad-leaved forest in  
27 Southern China. *Global Change Biology*, n/a-n/a.
- 28 Zhou, Y.P., Xu, K.M., Sud, Y.C., and Betts, A.K., 2011: Recent trends of the tropical hydrological cycle inferred  
29 from Global Precipitation Climatology Project and International Satellite Cloud Climatology Project data.  
30 *Journal of Geophysical Research-Atmospheres*, **116(D09101)**.
- 31 Zhu, K., Woodall, C.W., and Clark, J.S., 2012: Failure to migrate: lack of tree range expansion in response to  
32 climate change. *Global Change Biology*, **18(3)**, 1042-1052.
- 33 Zimov, N.S., Zimov, S.A., Zimova, A.E., Zimova, G.M., Chuprynin, V.I., and Chapin, F.S., 2009: Carbon storage in  
34 permafrost and soils of the mammoth tundra-steppe biome: Role in the global carbon budget. *Geophysical*  
35 *Research Letters*, **36**.
- 36 Zurell, D., Grimm, V., Rossmannith, E., Zbinden, N., Zimmermann, N.E., and Schroder, B., 2012: Uncertainty in  
37 predictions of range dynamics: black grouse climbing the Swiss Alps. *Ecography*, **35(7)**, 590-603.
- 38 Zyryanova, O.A., V. T. Yaborov, T. I. Tchikhacheva, T. Koike, K. Makoto, Y. Matsuura, F. Satoh, and V. I.  
39 Zyryanov, 2007: The structure and biodiversity after fire disturbance in *Larix gmelinii* (Rupr.) Rupr. Forests.  
40 *Northeasten Asia Eurasian Journal of Forest Research*, **10(1)**, 19-29.
- 41

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  $P \leq 0.05$ ).

	Location	Reference	Plots	Time Period	Shift type	Retracting biome	Expanding biome	Temp. change (°C century <sup>-1</sup> )	Precip. change (century <sup>-1</sup> )
1.	Alaska Range, Alaska, USA	Lloyd and Fastie, 2003	18	1800-2000	L	UA	BC	1.1*	0.03
2.	Baltic Coast, Sweden	Walther <i>et al.</i> , 2005	7	1944-2003	L	TC	TB	0.6*	0.08
3.	Becca di Viou, Italy	Leonelli <i>et al.</i> , 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 Fillion, 1985	2	1880-1980	E	UA	BC	1.4*	0.19*
6.	Green Mountains, Vermont, USA	Beckage <i>et al.</i> , 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 <i>et al.</i> , 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 Fillion, 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 <i>et al.</i> , 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 <sup>-1</sup> )	Precip. change (century <sup>-1</sup> )
15.	Putorana Mountains, Russia	Kirdyanov <i>et al.</i> , 2012	10	1500-2000	E	UA	BC	0.3	0.10
16.	Rahu Saddle, New Zealand	Cullen <i>et al.</i> , 2001	7	1700-2000	N	-	-	0.6*	0.03
17.	Rai-Iz, Urals, Russia	Devi <i>et al.</i> , 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 <i>et al.</i> , 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 <i>et al.</i> , 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
<b>8.5-MESSAGE</b>	<p>No climate change mitigation actions; radiative forcing still rising at 2100</p> <p>Strong increase in agricultural resource use driven by the increasing population (rises to 12 billion people by 2100)</p> <p>Yield improvements and intensification assumed to account for most of production increases</p>	<p><b>Increase in cultivated land by about 305 million ha from 2000 to 2100</b></p> <p><b>Forest cover declines by 450 million ha from 2000 to 2100</b></p> <p><b>Arable land use in developed countries slightly decreased - all of the net increases occur in developing countries.</b></p>
<b>6.0-AIM</b>	<p>Mitigation actions taken late in the century to stabilize radiative forcing at <math>6 \text{ Wm}^{-2}</math> after 2100</p> <p>Population growth and economic growth</p> <p>Increasing food demand drives cropland expansion</p>	<p><b>Urban land-use increases</b></p> <p><b>Cropland area expands</b></p> <p><b>Grassland area declines</b></p> <p><b>Total forested area extent remains constant</b></p>
<b>4.5-GCM</b>	<p>Mitigation stabilizes radiative forcing at <math>4.5 \text{ Wm}^{-2}</math> before 2100</p> <p>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</p> <p>Food demand met through crop yield improvements, dietary shifts, production efficiency and international trade.</p>	<p><b>Preservation of large stocks of terrestrial carbon in forests</b></p> <p><b>Overall expansion in forested area</b></p> <p><b>Agricultural land declines slightly due to afforestation,</b></p>
<b>2.6-IMAGE</b>	<p>Overall trends in land use and land cover mainly determined by demand, trade and production of agricultural products and bio-energy</p>	<p><b>Much agriculture relocates from high income to low income regions</b></p> <p><b>Increase in bio-energy production, new area for bioenergy crops near current agricultural areas.</b></p>

## 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.
- Kirilyanov, 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.

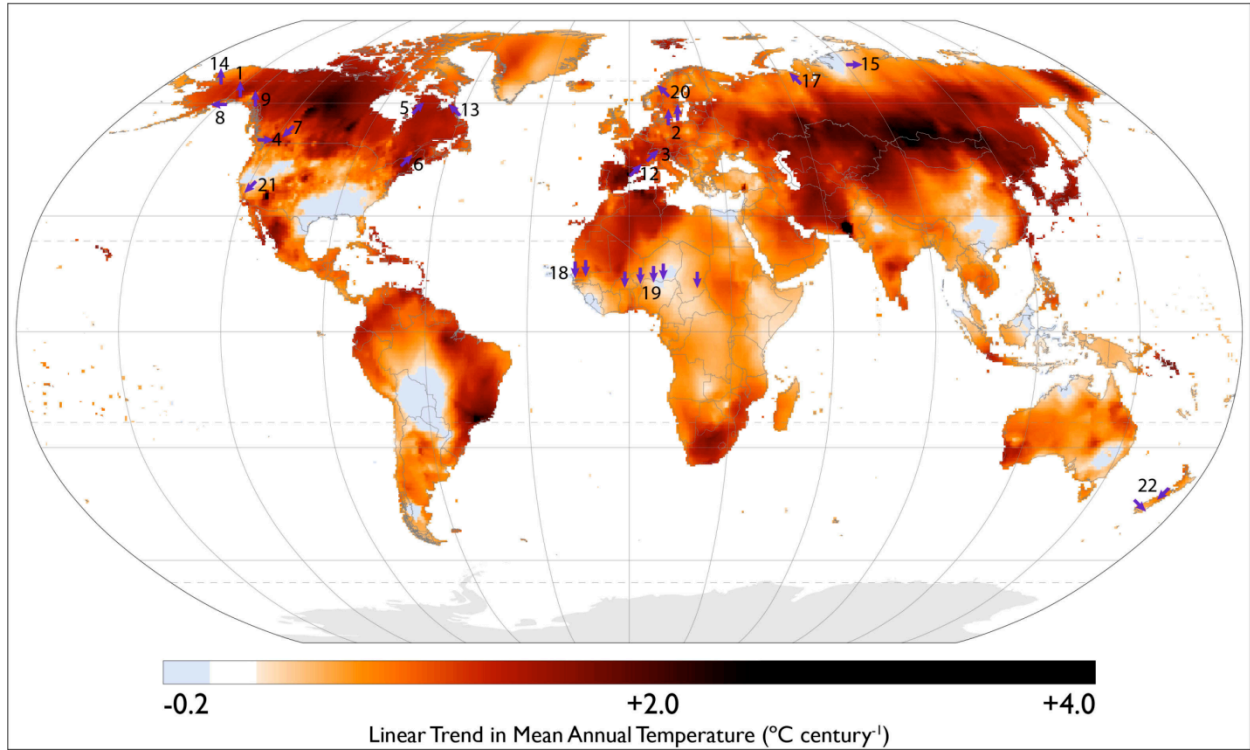


Figure 4-1: Biome shifts in the past.

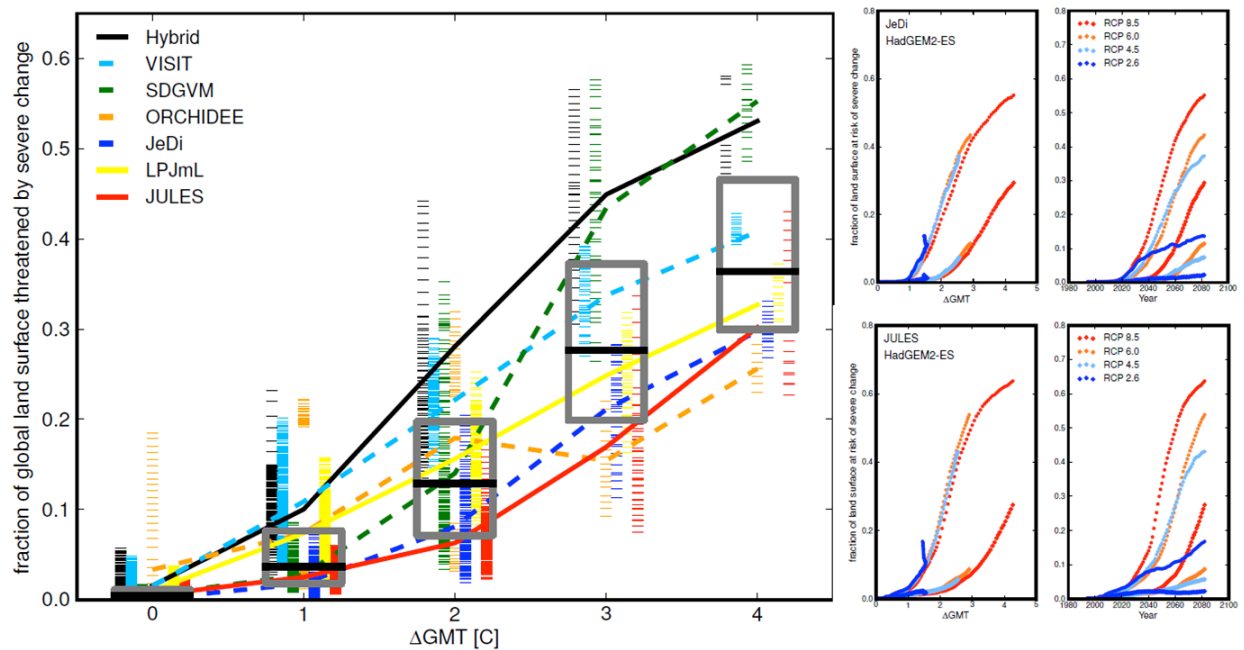


Figure 4-2: Fraction of land surface at risk of severe ecosystem change as a function of global mean temperature change for all ecosystems models, global climate models and RCPs

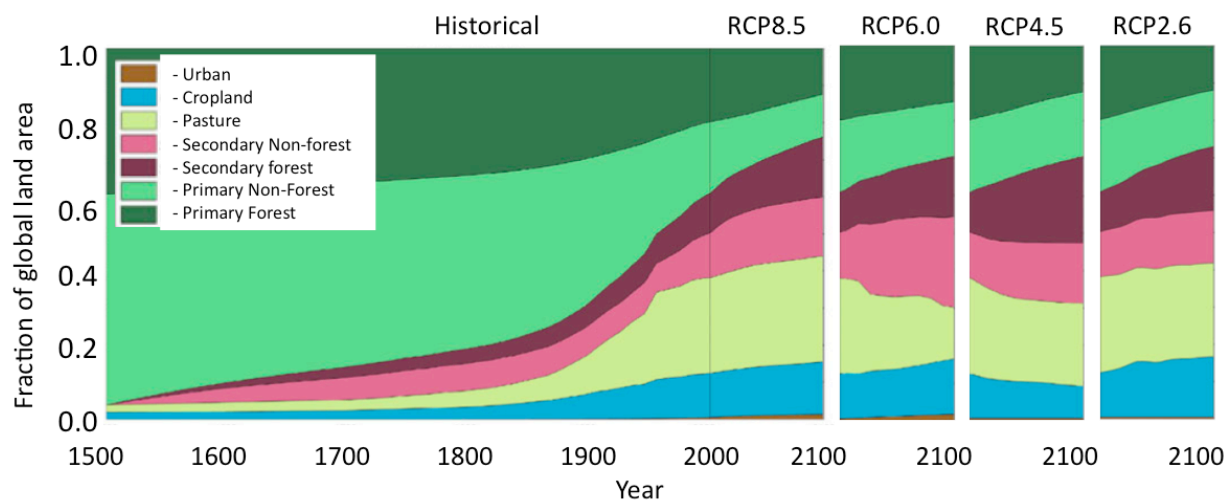


Figure 4-3: Proportion of global land cover occupied by primary and secondary vegetation (forest and non-forest), cropland, pasture and urban land, from satellite data and historical reconstructions up to 2005, and from scenarios associated with the RCPs from 2005 to 2100.

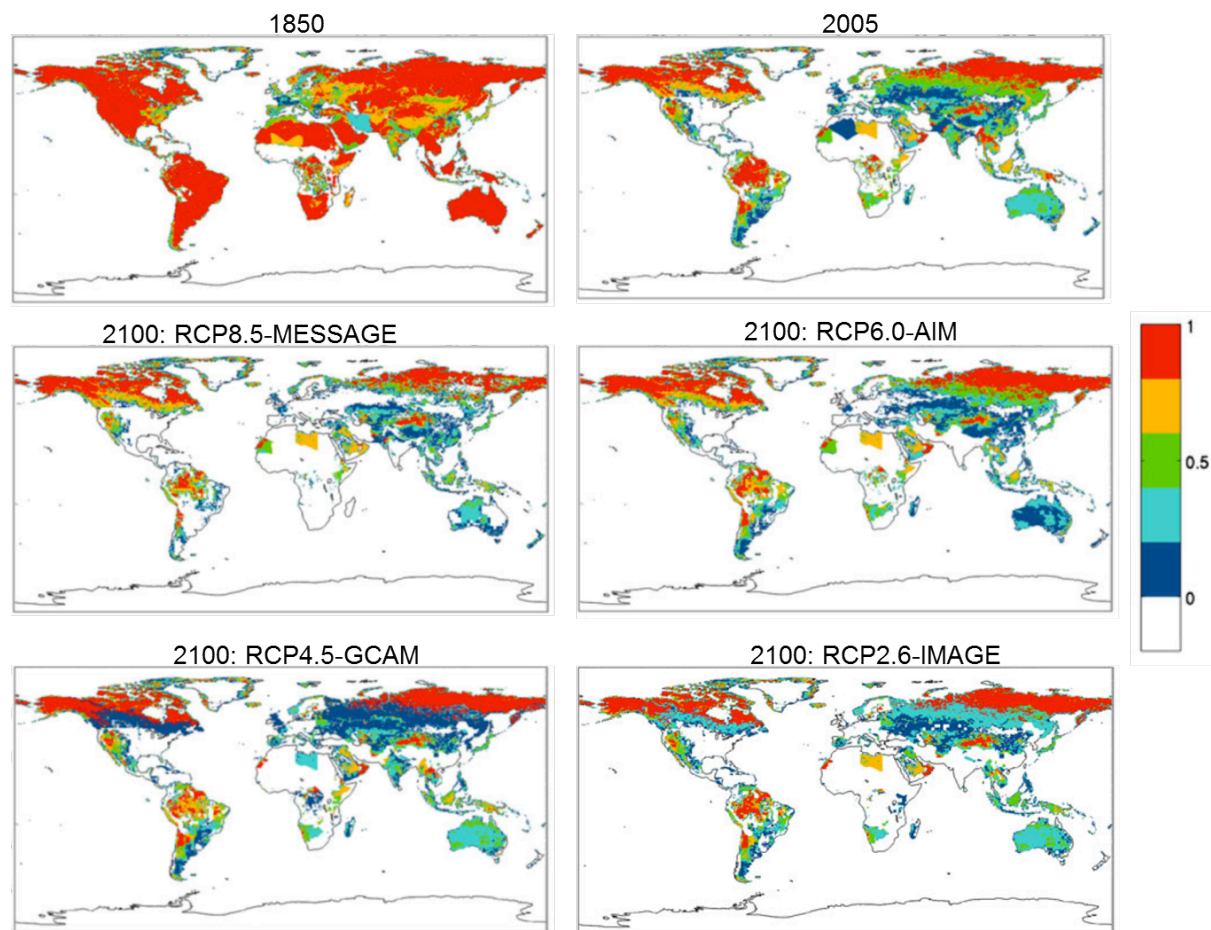


Figure 4-4: Fractional cover of primary vegetation at 1850 and 2005 based on satellite data and historical reconstructions, and at 2100 in scenarios associated with the RCPs.



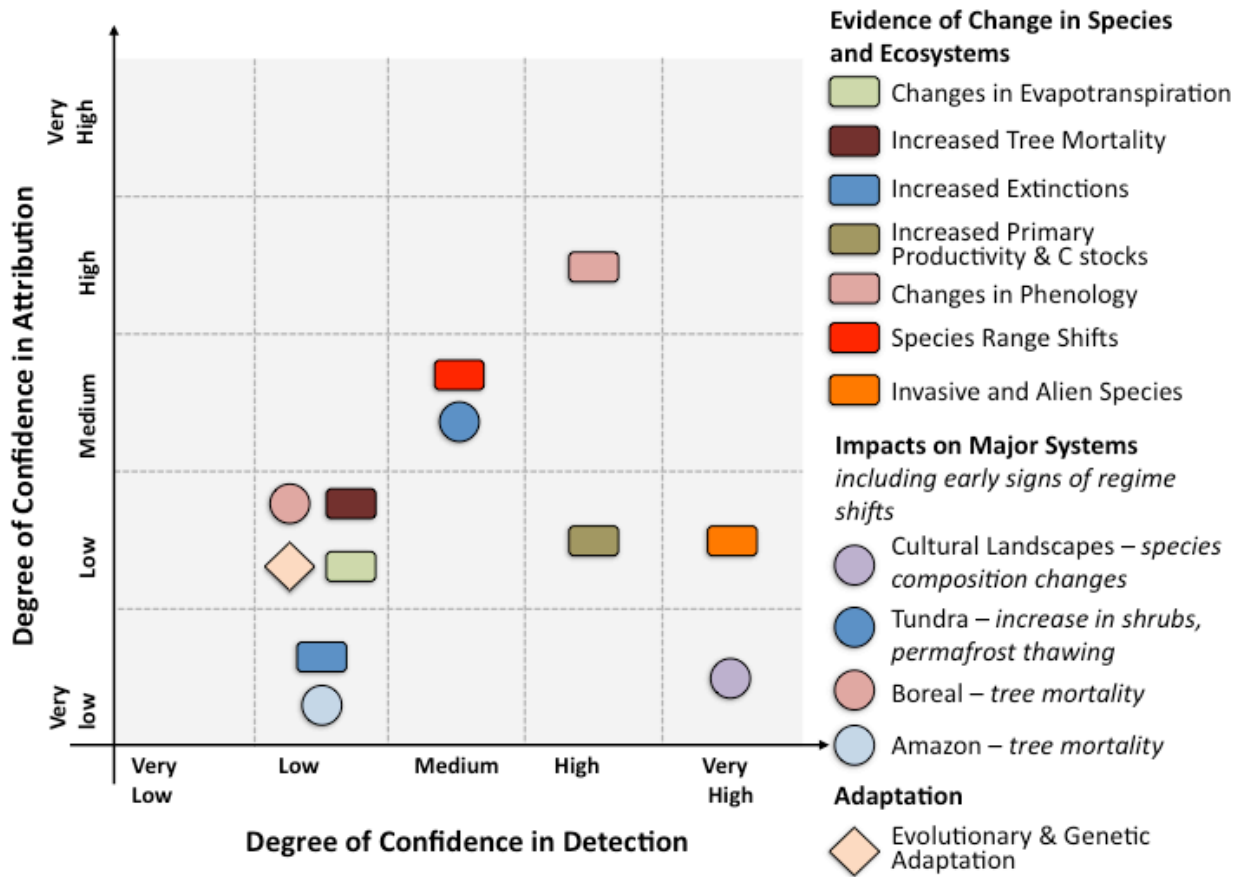


Figure 4-5: Confidence in Detection and Attribution of observed responses of terrestrial ecosystems to climate change.

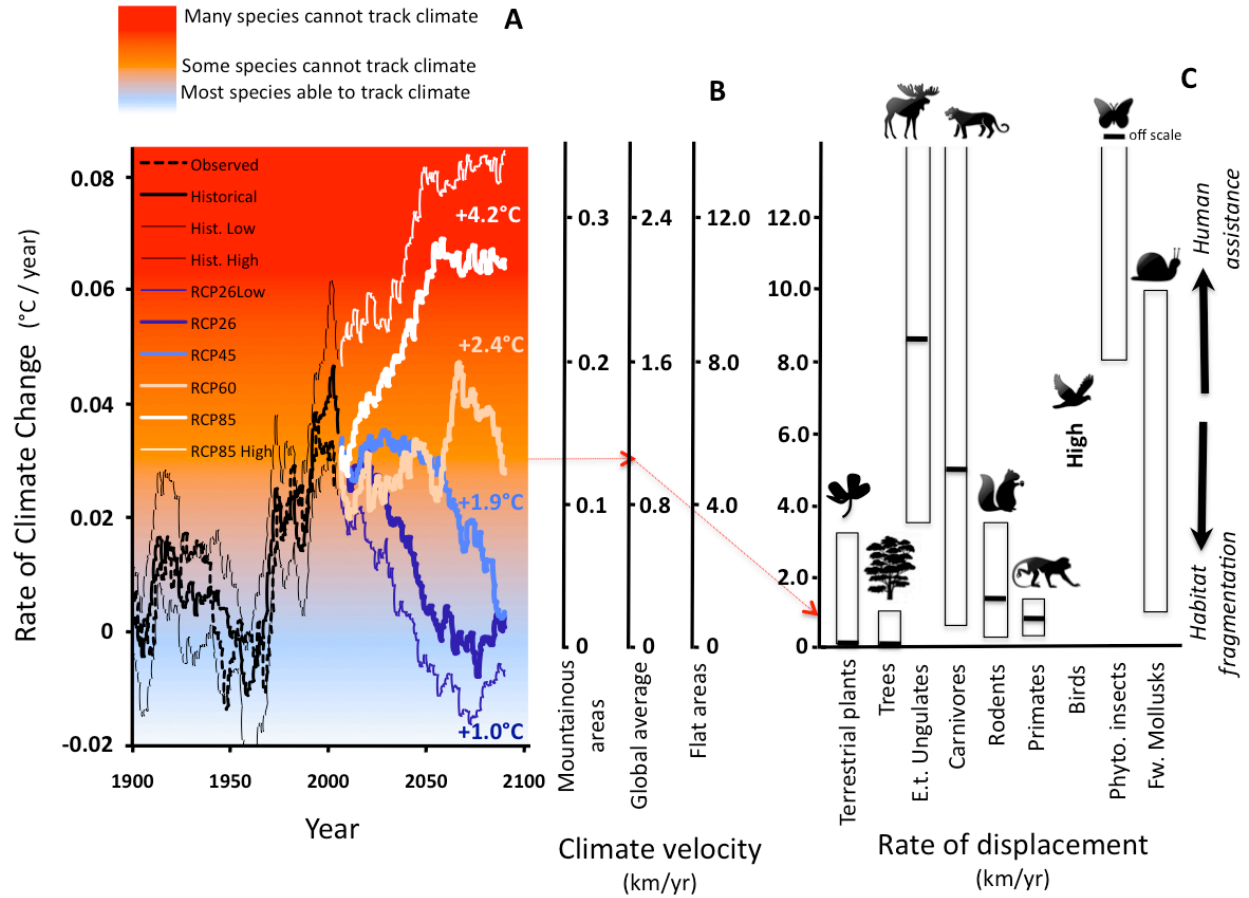
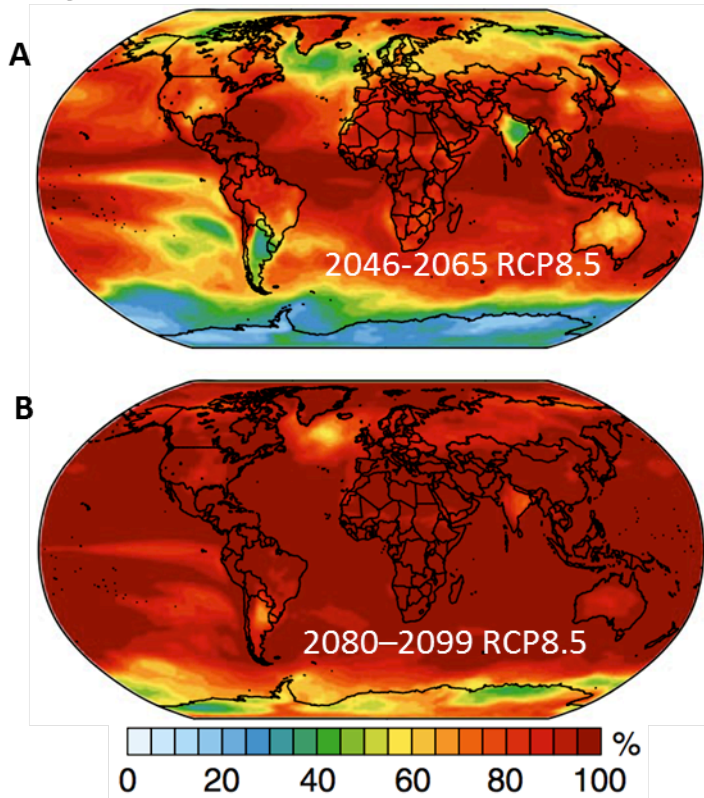
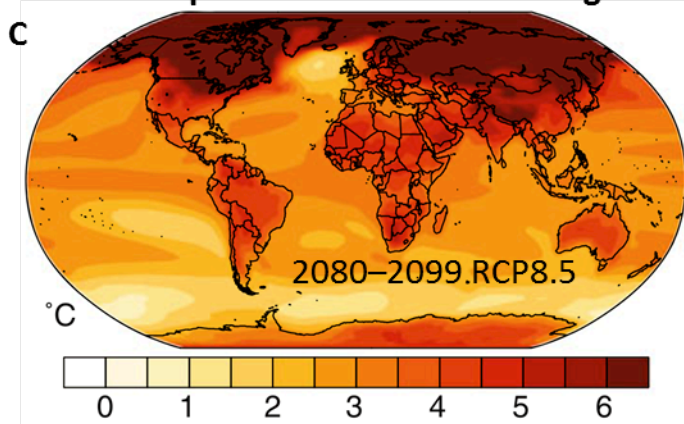


Figure 4-6: Rate of climate change, climate velocity and rate of displacement

**Percentage of years when June-August temperatures exceed the 1986–2005 maximum**



**Seasonal temperatures for December-February compared to 1986-2005 average**



From: Diffenbaugh & Giorgi. 2012. Climatic Change 114-813-822

Figure 4-7: Vulnerability of terrestrial biomes to future climate change.

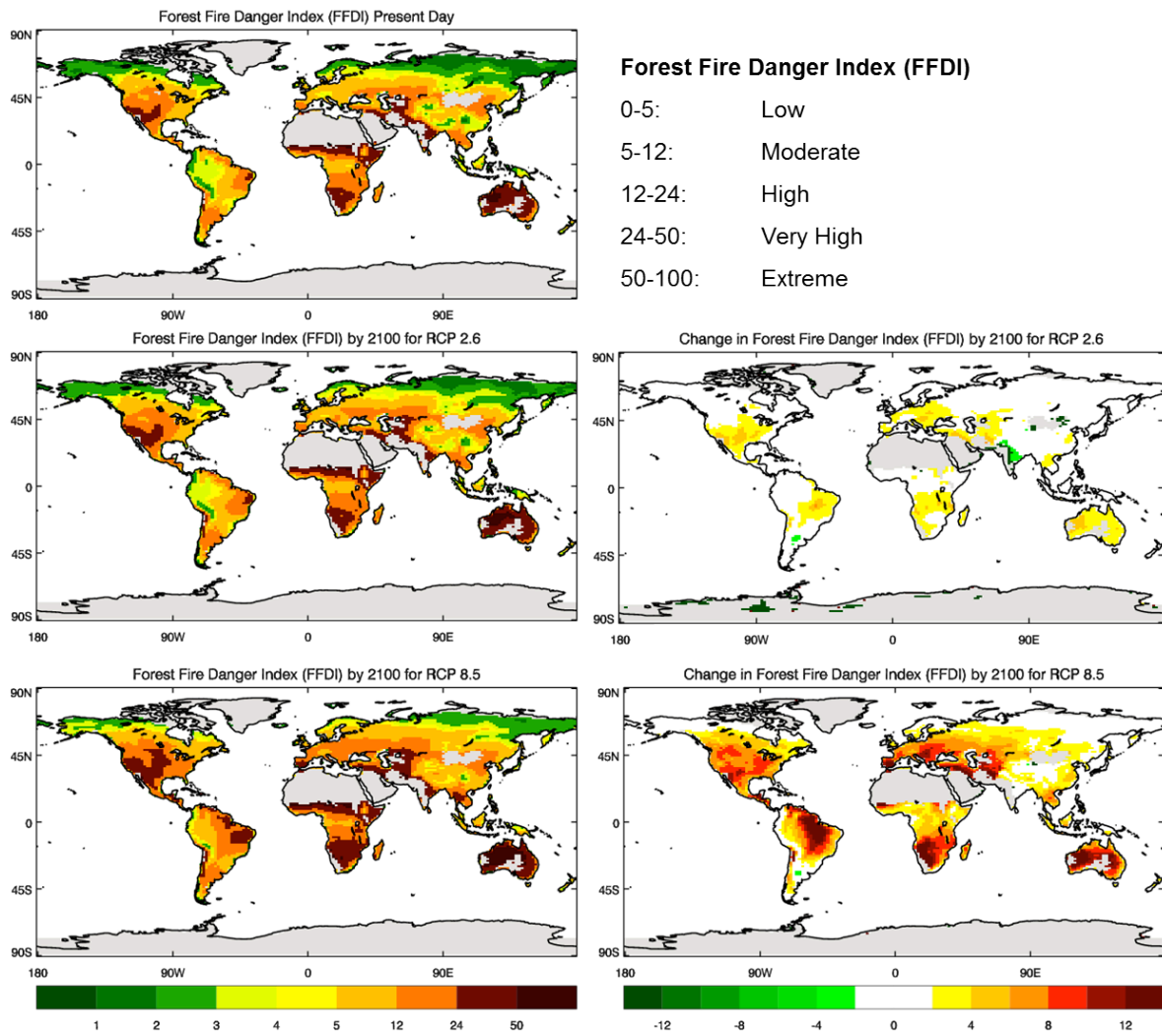


Figure 4-8: Forest Fire Danger Index simulated with the HadGEM2-ES Earth System Model.

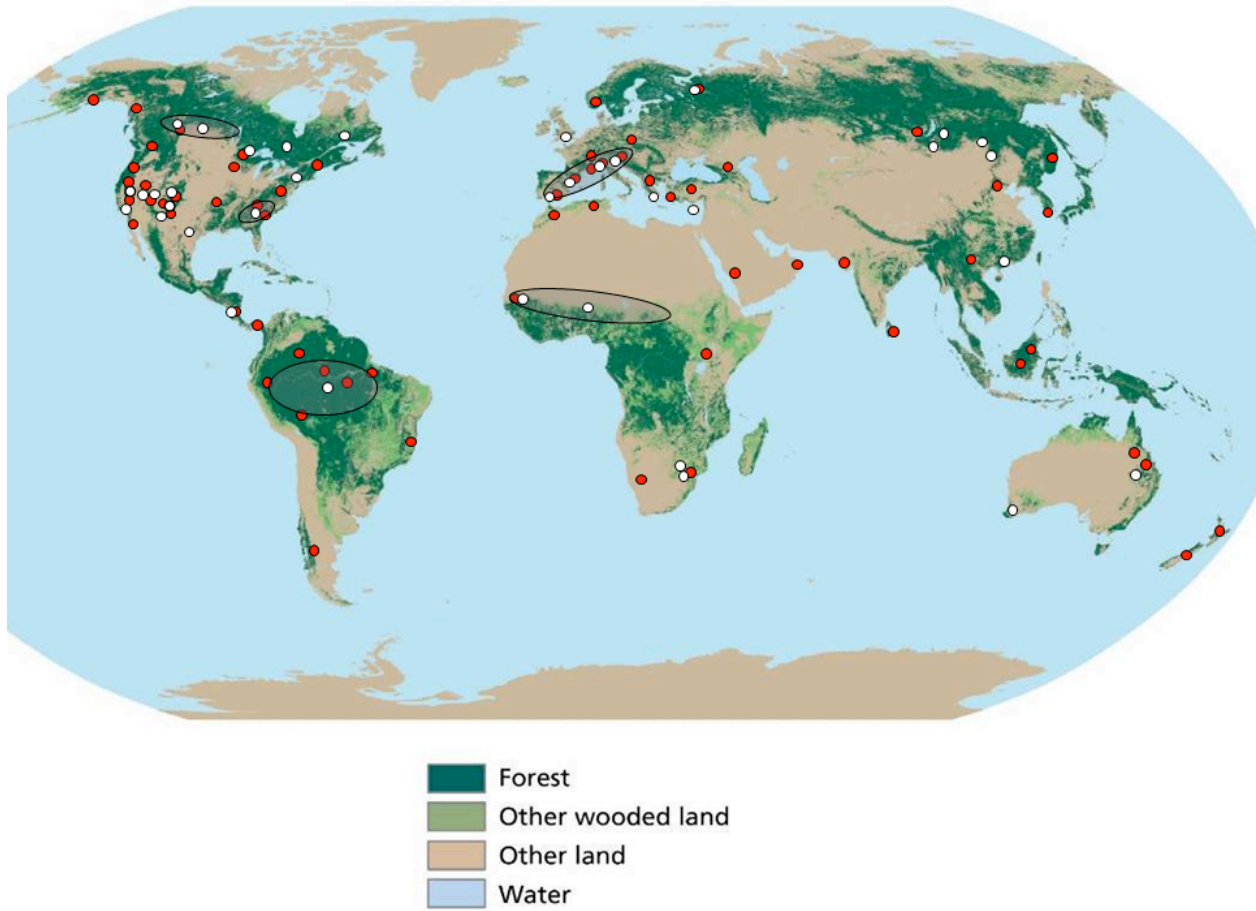


Figure 4-9: Forest mortality related to climatic stress.

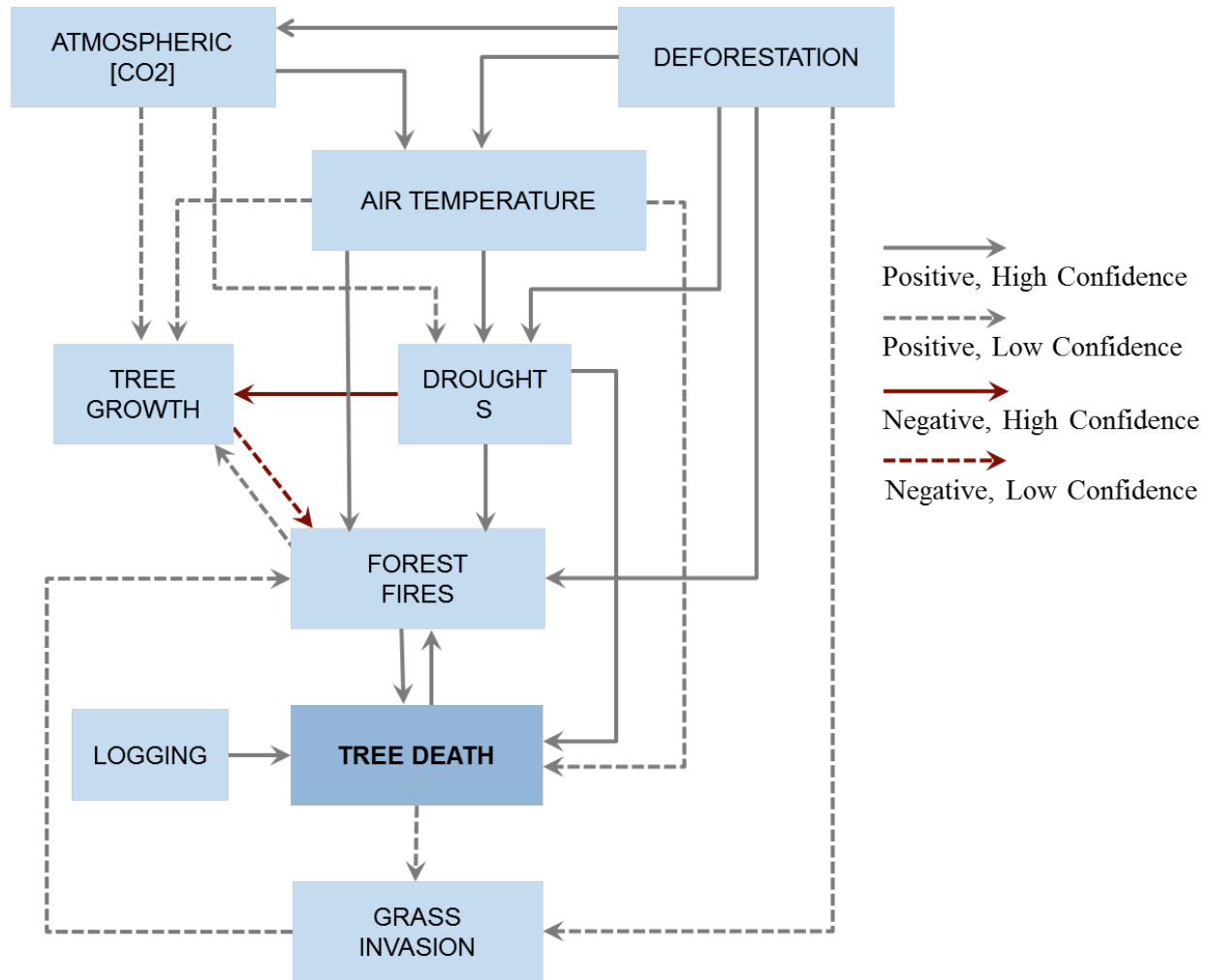


Figure 4-10: Amazon Die back.

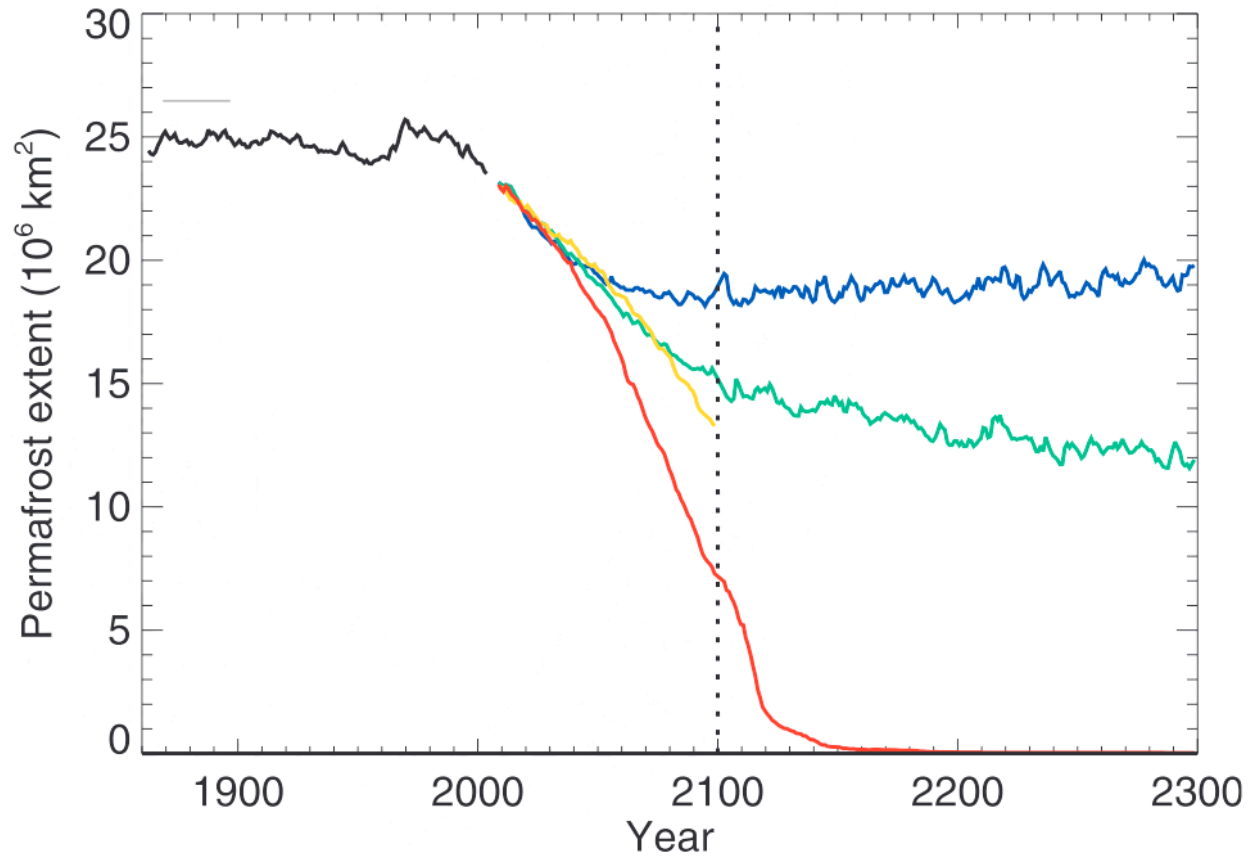


Figure 4-11: Simulations of past and future northern hemisphere permafrost area with a maximum thaw depth less than 3m deep.

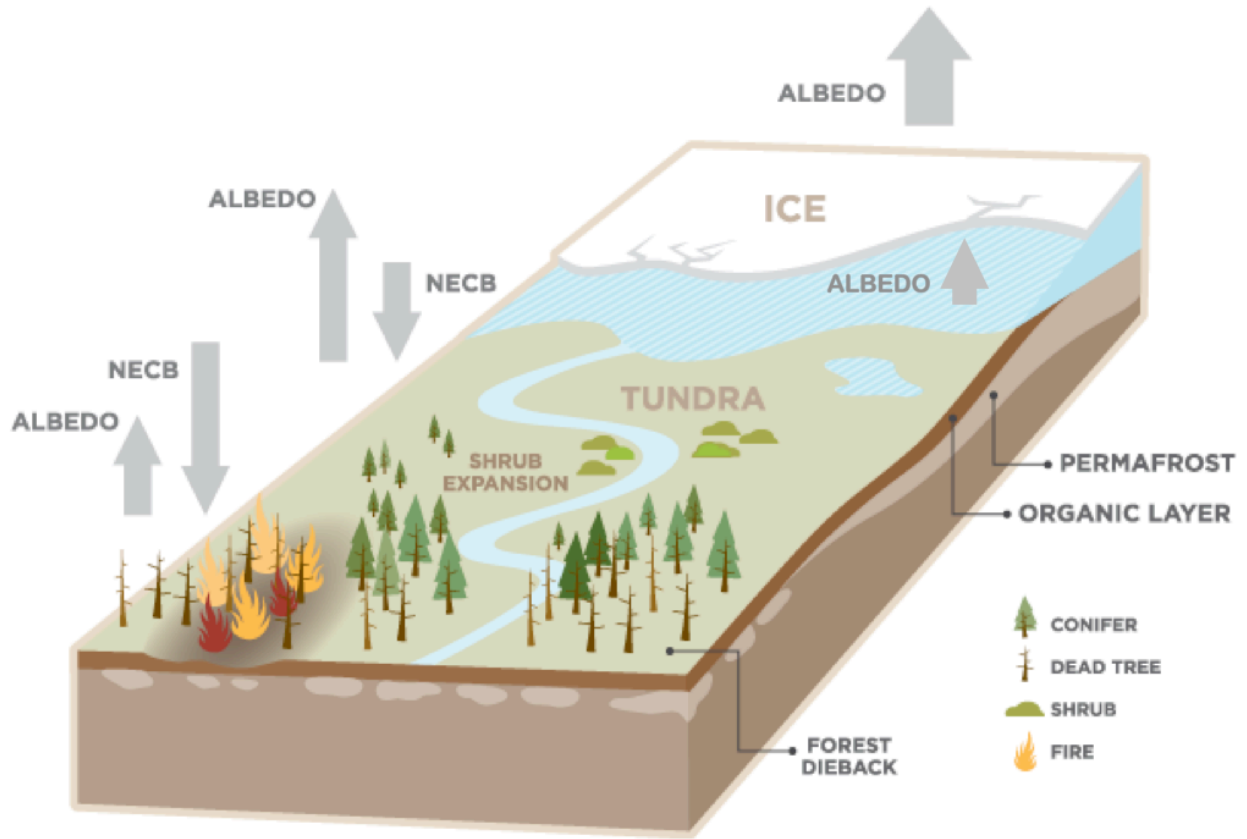


Figure 4-12: Tundra biome shift.



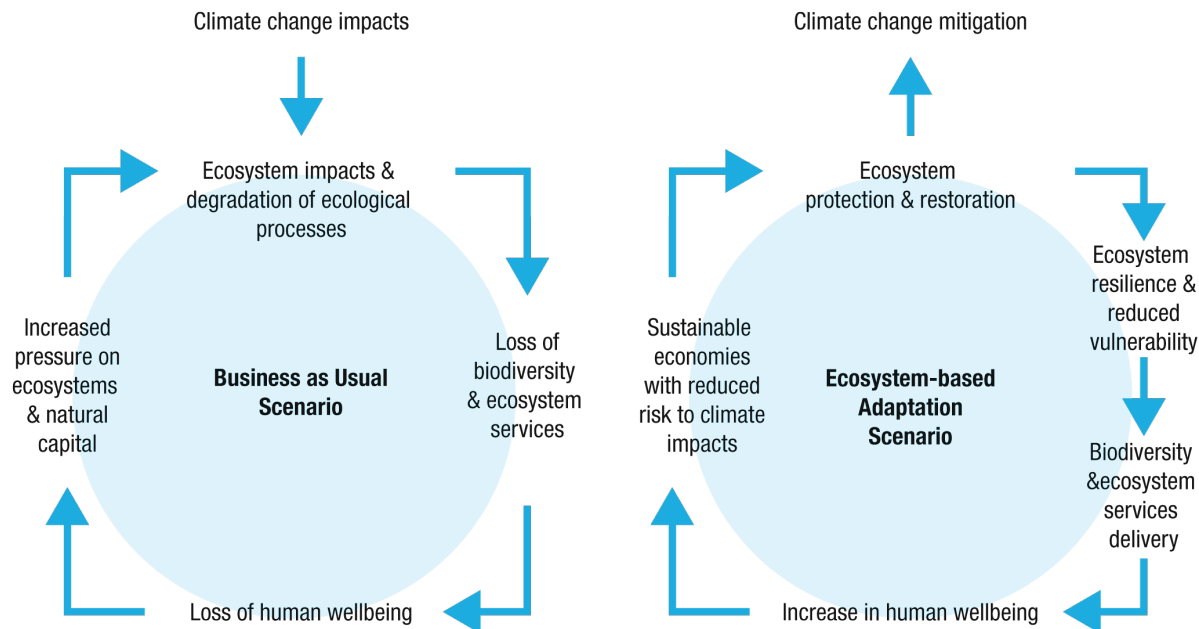


Figure EA-1: Adapted from Munang *et al.* (2013). Ecosystem based adaptation approaches to adaptation can utilize the capacity of nature to buffer human systems from the adverse impacts of climate change through sustainable delivery of ecosystems services. A) Business as Usual Scenario in which climate 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.

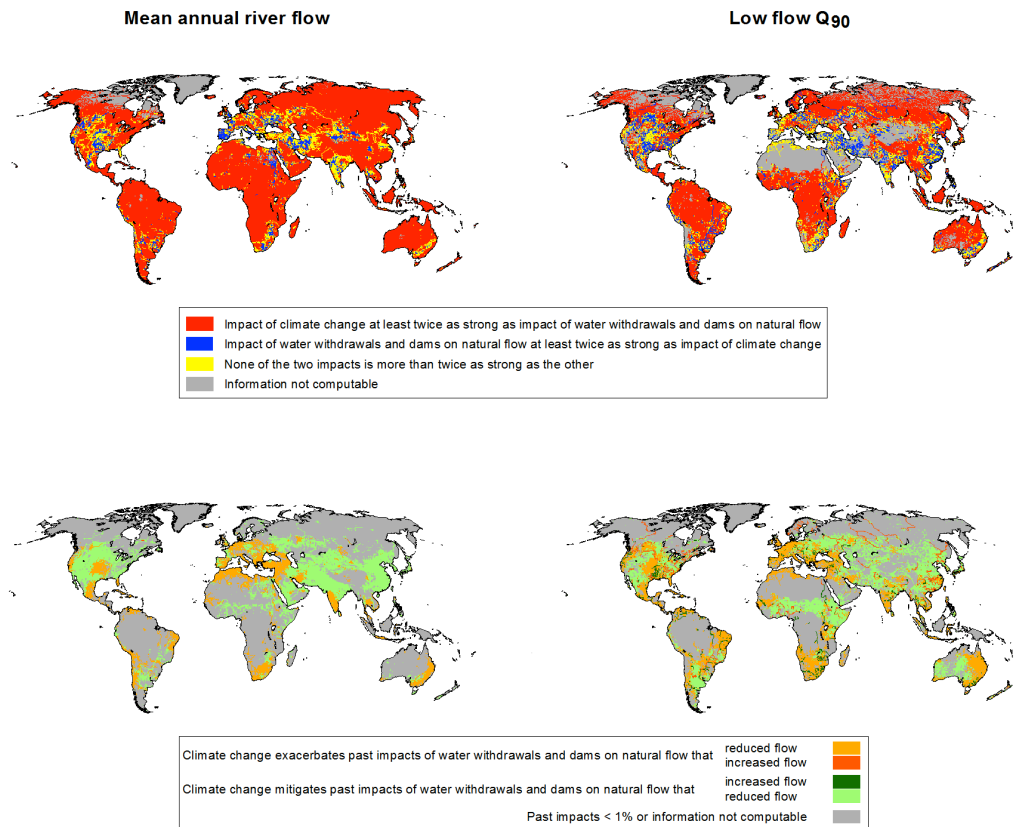


Figure RF-1: Impact of climate change on the ecologically relevant river flow characteristics mean annual river flow and monthly low flow  $Q_{90}$  as compared to the impact of water withdrawals and dams on natural flows, as computed by a global water model (Döll and Zhang, 2010). Impact of climate 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.

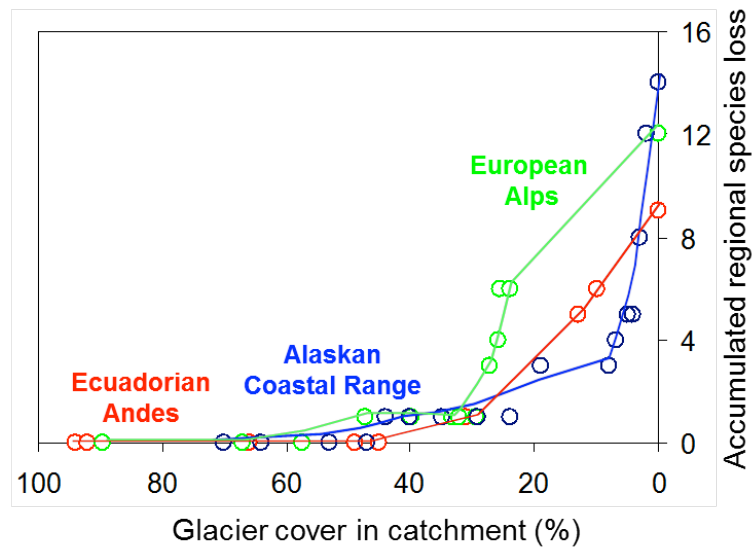


Figure RF-2: Accumulated loss of regional species richness (gamma diversity) as a function of glacial cover GCC. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%. Each data point represents a river site and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

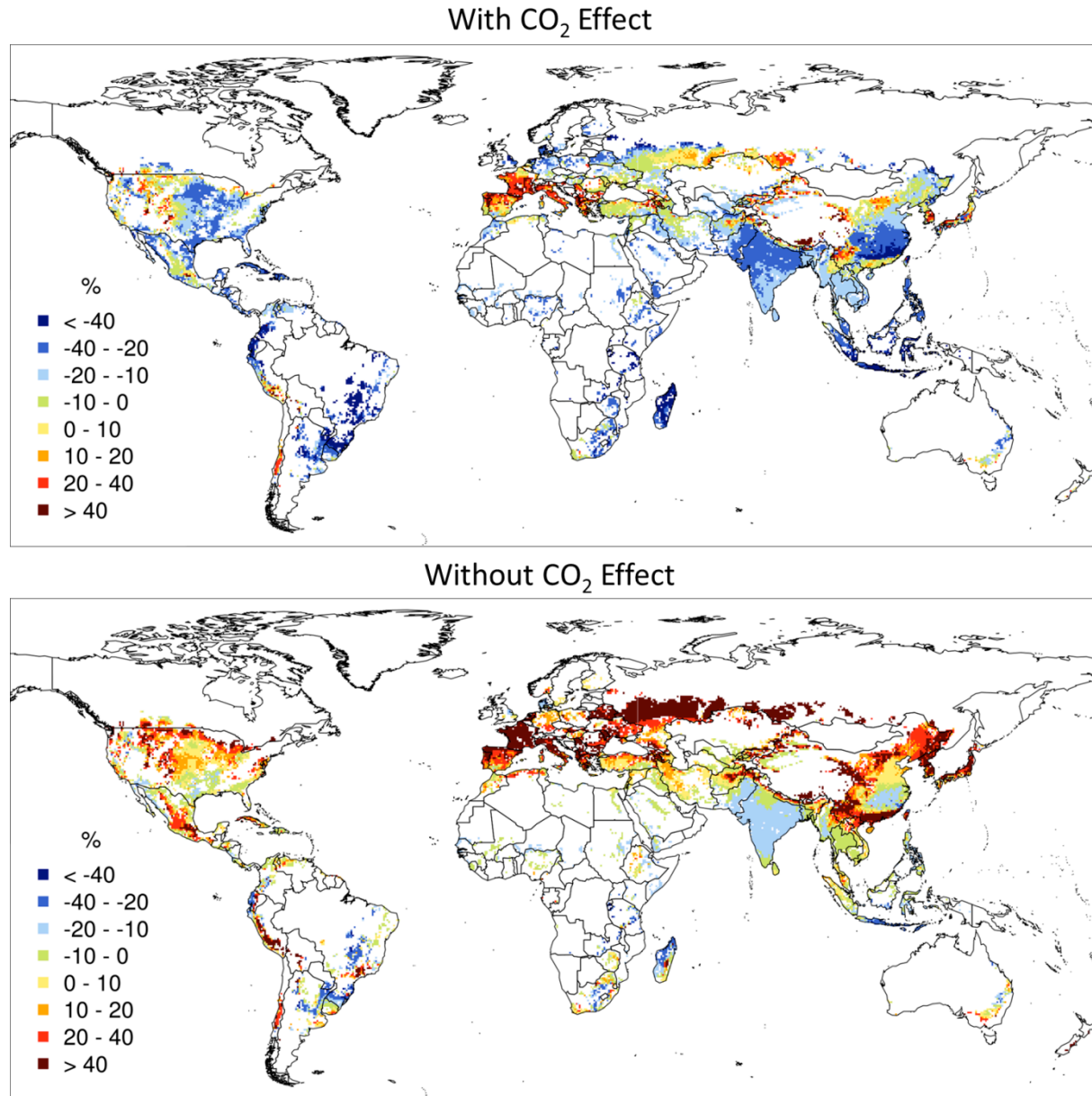


Figure VW-1: Percentage change (ensemble median across 19 GCMs used to force a vegetation and hydrology model) in net irrigation requirements of 12 major crops by the 2080s, assuming current extent of irrigation areas and current management practices. Top: impacts of climate change only; bottom: additionally considering physiological and structural crop responses to increased atmospheric CO<sub>2</sub> concentration. Taken from Konzmann *et al.* (2013).

**The global-scale water – energy – food – climate change nexus**

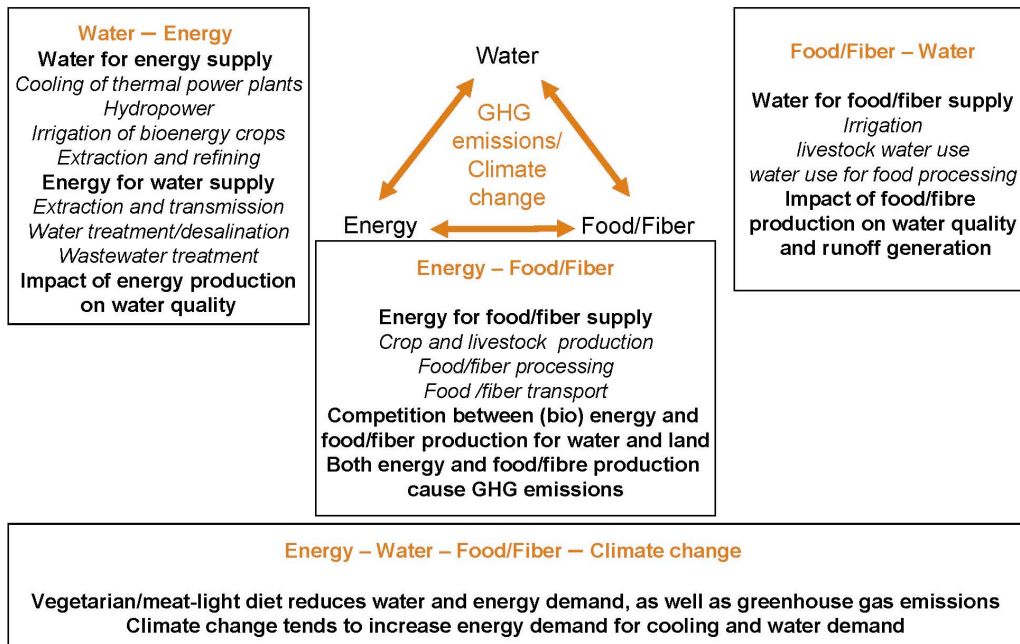


Figure WE-1: The water-energy-food nexus as related to climate change.